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PHYSICAL ASPECTS OF THREE-DIMENSIONAL WAVE REFLECTIONS IN TRANSONIC WIND TUNNELS AT MACH NUMBER 1.20 (PERFORATED, SLOTTED, AND COMBINED SLOTTED-PERFORATED WALLS)

(TITLE UNCLASSIFIED)

By

B. H. Goethert; PWT, ARO, Inc.

March 1956

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SUMMARY

A series of experimental and theoretical investigations associated with the testing of three-dimensional bodies of revolution in transonic test sections are discussed. This report presents test results obtained at a Mach number of 1.2 at which, for the cone-cylinder models considered, only attached shock waves occur.

The cone-cylinder tests conducted in the Transonic Model Tunnel (TMT) are a part of a systematic investigation of three-dimensional wave reflections in transonic wind tunnels (Refs. 1-3). It is shown that conventional slotted and perforated test sections do not produce satisfactory data at model blockage ratios of two percent. The main source of the difficulties was traced experimentally and theoretically to a substantial difference between the characteristics of a conventional perforated- or slotted-type test section and the wall characteristics required for interference-free flow. Both experiments and theory indicate that a differential-resistance type wall is required - that is, one with low resistance to outflow from the test section and with high resistance to inflow. A series of wall element studies resulted in developing a wall type which matches the required characteristics reasonably well. Test results for differential-resistance walls of both the pure perforated and the combination slotted-perforated type show that satisfactorily accurate data can be obtained for cone-cylinder models.

It is shown theoretically that model configurations which are more smoothly curved than cone-cylinder models will be less critical with regard to wall interference in transonic testing. For testing of model configurations with strong shock waves, the perforated test section of the differential-resistance type can be expected to be superior. On the other hand, for testing of smoothly curved models with weak shock waves, the combination slotted-perforated test section of the differential-resistance type can also be expected to produce reasonably interference-free results.

NOMENCLATURE

A	Area
c	Ratio of open to total area
D	Model diameter
H	Test-section height
h	Distance between slot centers
K, K_1, K_2	Wall constants
l	Height of slat protrusion into test section
Δl	Change in effective height of slat protrusion due to model blockage
M_∞	Mach number of undisturbed flow
p_o	Settling-chamber total pressure
p	Static pressure
Δp	Difference between local static pressure in test section and plenum chamber pressure
q	Dynamic pressure, $q = \frac{\rho}{2} v^2$
r	Radial coordinate
Vol	Volume of model
v_x	Velocity component in x-direction
v_y	Velocity component in y-direction
v_∞	Velocity of undisturbed flow
Δv_n	Disturbance velocity normal to tunnel wall
Δv_x	Disturbance velocity in flow direction
x	Coordinate in flow direction
y	Coordinate perpendicular to wall
z	Coordinate parallel to wall and perpendicular to flow direction
α	Inclination of hole from normal
$\theta_w = \frac{\Delta v_n}{v_\infty}$	Flow inclination at wall
ρ	Air density
$(\rho v)_w$	Cross-flow per unit wall area

INTRODUCTION

Previous investigations have shown that in the case of two-dimensional shock waves test-section walls can be developed which satisfactorily eliminate shock reflections (see Refs. 4, 5, and 6). At large distances behind the initial shock front, the cross-flow through such test-section walls produces a pressure drop across the wall just sufficient to maintain a pressure within the tunnel, in this region, that is equal to the static pressure behind the initial shock front. In other words, the characteristics of the wall are such that the direction of the flow is not changed by the tunnel wall, with regard to that in free-flight, as must be the case to obtain interference-free test results. Previous investigations (Refs. 4-6) have also shown that, with respect to two-dimensional shock cancellation, a perforated test-section wall has a greater potential than the longitudinally-slotted test-section wall, since a perforated wall with fixed geometry is capable of effectively reducing reflections of shock waves of different intensities at different Mach numbers. This was not found possible with a fixed-geometry slotted wall. To attain satisfactory shock cancellation with perforated walls, it has been found necessary to keep the boundary layer along the walls sufficiently thin to prevent boundary-layer shock interaction. This can be accomplished by simultaneously converging the walls and removing air from the plenum chamber surrounding the test section by means of suitable suction devices (Ref. 7).

Theoretical considerations have also indicated that the wall geometry of both slotted and perforated test sections for complete shock cancellation must be different for the region in the vicinity of the initial shock and for the region at a large distance behind the shock (see Ref. 4). This is not as serious a limitation as may first appear. In the case of a two-dimensional shock front, it can be shown that the length of the region, in which the transition from the undisturbed flow to the final flow downstream of the shock front and its secondary wave system occurs, is proportional to the distance between the holes of the perforated walls. Consequently, satisfactory reflection-free wind-tunnel results can be obtained in two-dimensional flow when, in walls with correct open-area ratio, the size of the holes is made sufficiently small.

However, for the case of three-dimensional wave fields, it has been shown theoretically that a perforated wall with constant geometry is not capable of completely eliminating wave reflections over the entire model region (see Ref. 4). At best, only a reasonably good compromise can be expected, which results largely from a fortuitous mixing of partial reflections of compression and expansion waves.

Several tests with complete airplane models have indicated, however, that indeed such a satisfactory compromise can be attained by using a perforated wall with constant geometry and boundary-layer removal.

In view of the lack of systematic data on three-dimensional wave-cancellation characteristics of wind-tunnel walls, it was decided to investigate a suitable series of three-dimensional models in the transonic and low supersonic speed ranges. The entire study was divided into several phases which have been investigated individually as separate problems. Through the combined efforts of several project engineers, it was possible to obtain more insight into the physical nature of the subject problem and to develop effective means of overcoming some of the serious difficulties occurring in transonic testing. The results of these individual studies, presented in Refs. 1-3, are summarized and discussed in sections II, III, and IV. In the remaining sections of this report, the results of additional studies of the testing capabilities in various transonic test sections with slotted, perforated, and combined slotted-perforated walls are presented. This report is restricted to the presentation and discussion of results obtained for various three-dimensional models at the Mach number 1.2. The kind of difficulties encountered and the means to overcome them, however, are typical for the entire range of the investigations.

II. CONE-CYLINDER INVESTIGATIONS IN PERFORATED TEST SECTIONS

A systematic series of cone-cylinder models with different cone angles and different blockage ratios were investigated in the TMT with different perforated test sections in the Mach number range between 0.75 and 1.25 by Gray and Gardenier (Ref. 1). In these tests, significant wall interaction difficulties were observed in the supersonic speed range, and they could be traced back to the mismatch between the wall characteristics of a conventional perforated wall and those required for effective cancellation of compression and expansion waves emanating from the model.

A. PRESSURE DISTRIBUTION AT MODEL SURFACE

Presented in Fig. 1 is the experimental pressure distribution for a 2-percent blockage cone-cylinder model in a perforated test section with 12-percent open area. Hole diameter and wall thickness were each 1/16 of an inch, and the wall setting was parallel to the centerline of the test section. It can be seen that the compression waves

originating from the conical flow field of the model were reflected as compression waves. From consideration of the initial and the reflected wave system and after comparison with theory (Ref. 2), it can be concluded that the wall with 12-percent open area is too closed.

Consequently, perforated test sections with 22- and 33-percent open areas, with the same hole size and wall thickness and parallel wall setting, were also investigated. Figure 2 shows that the 22-percent open wall very nearly eliminated wave reflections in the compression-wave region (x/D = 3.6 to 5.6), whereas the 33-percent open wall was definitely too open since the compression waves were reflected as expansion waves in this region. Further observation of Fig. 2, however, indicates that behind the compression-wave region, from which reflection waves can be expected on the model approximately 5.6 diameters behind the nose, another even more serious disturbance region occurs with the 22- and 33-percent open walls. These disturbances can be traced to the expansion waves originating from the shoulder of the model and are even greater in magnitude than the disturbances observed in the compression-wave region. The nature of these expansion-wave disturbances implies that the more open walls of 22- and 33-percent open area reflect the expansion waves as compression waves or, as the magnitude of the observed compression disturbances indicates, that a concentrated inflow into the test section produces a flow inclination considerably larger than does interference-free flow.

The cone-cylinder test results obtained in perforated test sections with different open-area ratios at parallel-wall setting have shown that it is possible to select a wall geometry which satisfies the condition of no-reflections in the compression-wave region. It is also possible to select a wall geometry which makes the expansion-wave reflections disappear. However, none of the conventional perforated walls will satisfy the no-reflection requirement in both the compression and expansion regions as is generally required in wind-tunnel testing.

Basically the same conclusion can be drawn from the experiments with the same walls of 12-, 22-, and 33-percent open areas when the walls are converged to approximately - 30 minutes or diverged up to +30 and +40 minutes (see Figs. 3 and 4).

It must be concluded, therefore, that conventional perforated walls, which were satisfactory for the testing of models with two-dimensional shock waves and for the testing of some complete airplane models, are not capable of producing satisfactory reflection-free data for the selected cone-cylinder model.

B. SURVEY OF REFLECTED WAVE SYSTEM

To gain more specific insight into the origin of the observed disturbances, the flow field at various distances from the model was surveyed; and in this way the disturbances were traced to their origin. In Fig. 5, for example, some typical survey results are presented in the case of a cone-cylinder model with 2-percent blockage in the perforated test section having 22-percent open walls. It can be recognized that the initial shock wave produced only a slight disturbance on the surface of the model (point 1b). Furthermore, it can be clearly seen that the entire compression-wave field, between the initial shock wave and the expansion-wave system from the shoulder, was properly absorbed by the walls since the experimental and the theoretical curve coincide very closely in this region. Strong disturbances, however, occurred in the region between the points 2b and 3b. They can be clearly traced to a reflection of the expansion waves as compression waves or, from a different viewpoint, as too large an inflow into the tunnel in the expansion-wave region. The major difficulty in testing a cone-cylinder model in the selected perforated test section, therefore, did not arise in attempting satisfactory absorption of the compression-wave system but in eliminating simultaneous reflections produced by the strong expansion-wave system originating at the shoulder of the model.

Difficulties similar to those described in the preceding section also occurred in the testing of a smaller cone-cylinder model with only 1/2-percent blockage in a 33-percent open perforated test section (see Fig. 6). Because of the large open-area ratio of the wall, the compression-wave system was reflected as an expansion-wave system, as is evidenced by the pressure distribution between the points 1b and 2b at the surface of the model. Furthermore, in the region influenced by reflections of the expansion wave system - that is, between points 2b and 3b - very significant disturbances occurred which are in the nature of reflections from walls that are too open. As before, these disturbances could be traced back to an excessively large inflow in the expansion-wave region along the tunnel wall.

The surveys presented above are for some typical examples and confirm the conclusions drawn in the previous section, namely, that conventional perforated walls are not capable of simultaneously eliminating reflections of both compression waves and expansion waves produced by a three-dimensional cone-cylinder model.

III. CONE-CYLINDER INVESTIGATIONS IN LONGITUDINALLY-SLOTTED TEST SECTIONS

To obtain insight into the wall-interference characteristics of typical test sections with longitudinal slots, the same cone-cylinder model with 2-percent blockage which was used in the perforated test sections was also investigated in various slotted test sections.

A. CONVENTIONAL SLOTS

Detailed slot-shape and empty test-section characteristics for a typical TMT test section with 16 uncovered longitudinal slots of 11-percent open area are described in Ref. 8. Some results of the cone-cylinder investigations (Ref. 1) in this test section are presented in Fig. 7. The comparison of the experimental pressure distributions along the surface with theoretical free-flight distributions indicates that the agreement between experiment and theory is even worse than for the corresponding experiments in conventional perforated test sections. It is particularly noteworthy that a large discrepancy between experiment and theory starts at a point on the surface of the cone (point 1b), which is considerably ahead of the point where the initial conical shock would be expected to be reflected against the surface of the model. The disturbance wave pattern which produces the observed discrepancies upstream of the initial conical shock indicates that a secondary flow in the slots occurred (discussed by Allen and Spiegel in Ref. 9). The occurrence of the secondary flow field can be attributed to the layer of subsonic flow close to the walls and in the slots. Although in supersonic flow a sudden pressure rise by means of shock waves is possible, such a sudden pressure rise is not possible in subsonic flow. Particularly in the subsonic flow region the pressure increase caused by impinging shock waves is propagated upstream in the flow. Consequently, a new boundary for the supersonic flow and a secondary wave system are established as indicated in Fig. 8.

Besides the disturbances which are produced directly by the secondary flow field, it can also be noted in Fig. 7 that both very strong expansion and compression waves impinge on the model further downstream, resulting in serious deviations from the theoretical flow field.

It can be concluded that a conventional longitudinally-slotted test section is even less capable of producing satisfactory interference-free results for the selected test conditions than conventional perforated test sections.

B. SLOTS WITH PERFORATED COVER PLATES

One major difficulty in testing cone-cylinder models in slotted test sections was found to be connected with the fact that a strong interference effect of the walls is observed upstream from the model-initiated shock waves. It was pointed out that this upstream effect is caused by the longitudinal flow, which, in the neighborhood of the slots is mainly subsonic and, consequently, cannot support sudden pressure changes as does supersonic flow. In order to find a remedy for this difficulty, further tests were carried out with perforated cover sheets placed over the longitudinal slots, cover sheets like those, for instance, employed in the WADC 10-foot wind tunnel (see Refs. 4 and 10). These cover plates are similar in principle to the corrugated plates in the slots employed in the test of Allen and Spiegel (Ref. 9). Their purpose is to reduce the secondary flow in the slots and to prevent, thereby, the upstream propagation of disturbances. Since it has been verified that perforated walls reduce the axial momentum of the flow on the outside of the walls to a negligibly small magnitude (Ref. 11), the cover plates may be expected to operate similarly and to accomplish their purpose.

The wind-tunnel tests of the cone-cylinder model with 2-percent blockage were conducted in a slotted test section with 16 longitudinal slots which were covered by perforated sheets with an open area of approximately 33 percent. Hole diameter and thickness of the perforated sheets were each 1/16 inch. The area ratio of the slots was 30 percent, which in connection with the 33-percent-open cover sheets, produces a geometric open-area ratio of 10 percent. This open-area ratio is approximately equal to the open-area ratio of the conventional slotted wall discussed in the preceding sections (see Fig. 7). A typical pressure distribution from these tests is represented in Fig. 9. The results indicate that no disturbances due to a secondary slot flow can be detected. The pressure distribution coincides very well with the theoretical pressure distribution upstream from the point where the initial conical shock reflection hits the model. In the compression-wave reflection region, $x/D = 3.6$ to 5.6, the test results indicate that the selected wind-tunnel wall is too closed since the compression waves produced by the model are reflected as compression waves. In the region behind the expansion-wave reflection, $x/D > 6.5$, the pressure distribution coincides satisfactorily with the theoretical distribution.

These tests verified the fact that a slotted test section with perforated cover sheets over the slots is capable of eliminating effectively the secondary flow disturbances previously discussed. However, it is necessary to open the walls more than for the conventional slotted con-

figuration in order to eliminate reflections in the compression-wave region.

In order to produce a test section with a proper open area for successful absorption of compression waves, it was necessary to increase the slot width to as much as 53 percent of the wall area and to diverge two walls of the test section to +30 min. As Fig. 9 indicates, the test results for such a wall configuration match closely the theoretical distributions in the region of compression-wave reflections. However, in the expansion-wave region the wall is considerably more open than is desirable. In this region, compression-wave disturbances caused by reflections of the expansion waves or by too large local inflows into the test section produce erroneous results, as in the case of a conventional perforated test section.

The results of cone-cylinder tests in slotted test sections have shown that, as was true for conventional perforated test sections, a wall configuration consisting of longitudinal slots with perforated cover plates can be devised which would eliminate the wall interferences in either the compression- or the expansion-wave region. However, no satisfactory slotted-wall configuration with conventional perforated cover plates over the slots has been found to eliminate simultaneously wave reflections in both the compression- and the expansion-wave regions.

IV. THEORETICAL FLOW PATTERN FOR VARIOUS THREE-DIMENSIONAL BODIES IN FREE-FLIGHT AND IN PERFORATED TEST SECTIONS

To aid in the understanding of the disturbances which were observed in the experiments with cone-cylinder models in perforated and slotted test sections, a theoretical study was initiated for determining the undisturbed flow characteristics of cone-cylinder and other models in a plane corresponding to the wind-tunnel walls. These calculations, carried out by DuBose and reported in Ref. 2, resulted in information on the distribution of the disturbance velocity and the disturbance flow inclination for interference-free flow. Since at a Mach number of 1.2 the bow shock on the cone-cylinders discussed in this report is attached, the entire flow field could be constructed by the method of characteristics.

A. CONE-CYLINDER MODEL

A sketch showing schematically the compression and expansion wave pattern around a cone-cylinder body in free-flight is presented in

Fig. 10a. In contrast to the wave field for a two-dimensional wedge, flat-plate body, this wave system consists not only of an initial shock and a following system of expansion waves initiating at the shoulder of the body, but also of a secondary wave system covering the entire three-dimensional flow field which is produced in order to satisfy the continuity requirements for wave fronts proceeding in a three-dimensional flow field. The pressure distribution in free-flight along a plane which would correspond to the wind-tunnel wall for a 2-percent blockage model indicates that, as pointed out in Ref. 4, only a small portion of the compression occurs in the initial conical shock (point A in Fig. 10b). The major portion of the compression occurs in the system of secondary compression waves downstream of the initial conical shock. The compression along the tunnel wall is abruptly interrupted by the expansion-wave system which causes the pressure to drop rapidly to values below the pressure of the undisturbed flow (region B-C). Behind this expansion-wave system, the pressure gradually returns to the undisturbed pressure.

Figure 10c presents the pressure disturbance as a function of the flow inclination along the same boundary plane. As pointed out in Ref. 4, the characteristic curve, $\Delta p/q = f(\theta_w)$ (that is, pressure disturbance is a function of flow inclination) is no longer represented by a straight line as in the two-dimensional case (linearized Pradtl-Meyer theory). Some noteworthy features of the characteristic curve are as follows:

1. The compression waves upstream from the expansion-wave system (region A-B) increase the pressure and the flow-inclination angle so that the flow angles for a given pressure rise are considerably larger than the values according to the Prandtl-Meyer curve.

2. In the expansion-wave region (region B-C), the pressure drops rapidly to values below the undisturbed pressure. At the point where the pressure has reached the undisturbed value, that is, at $\Delta p/q = 0$, the flow still has an inclination of 0.7°, pointing away from the body. At zero flow inclination, $\theta_w = 0$ (flow parallel to the cone-cylinder axis), the disturbance pressure is negative; that is, the local pressure is smaller than the static pressure of the undisturbed flow. Progressing downstream in the negative pressure region, the flow attains flow inclinations which point toward the body (inflow) and reach absolute magnitudes only slightly smaller than those in the outflow region (point C).

3. In the inflow region, particularly in the region C-O, the pres-

sure deviates even more strongly from the linear characteristics since considerably lower static pressures occur than predicted by linearized Prandtl-Meyer theory.

Since the characteristics of a perforated wall can be represented approximately by a straight line, it is obvious that the boundary conditions for a disturbance-free tunnel wall cannot be obtained with a perforated wall for the type of flow under consideration. It appears possible that, in the compression region (region A-B), the necessary boundary condition can be approximated by a wall which has a linear pressure-drop characteristic similar to that of a perforated wall. In the expansion region, however, such a wall is not capable of satisfying the boundary conditions because large deviations from the Prandtl-Meyer flow occur. Moreover, in the region of negative pressure, the correct boundary condition calls for outflow, inflow, or parallel flow, depending upon the wall station under consideration. It is obviously impossible to attain all these conditions when testing with the same perforated wall of constant geometry. It can be concluded, therefore, that the flow field around a cone-cylinder model in a conventional perforated test section will be distorted because inflow into the test section will occur in the region where the theory requires outflow. Consequently, strong compression disturbances originating in this region must be expected.

Comparison of the theoretical results with the experiments discussed in Section II makes it apparent that the experiments corroborate the theoretical flow pattern.

A part of the observed inflow difficulties could be overcome if a perforated wall could be designed which would resist the flow into the test section more than it would the flow out of the test section. With such a differential-resistance wall, it appears possible that simultaneous matching in the outflow as well as in the inflow field could be realized over large regions. Even in this case, however, it must be expected that a small region of mismatch will exist in the middle of the expansion-wave system (Fig. 10, region B-C) because a perforated wall, though of the differential-resistance type, still cannot support negative pressures in the test section with the flow proceeding outward against the higher pressure in the surrounding plenum chamber.

B. VARIOUS BODIES OF REVOLUTION WITH DIFFERENT CONTOURS

As pointed out in the preceding section, the main source of interference in testing a cone-cylinder model in perforated test sections is associated with the expansion-wave system initiated at the shoulder of the model. If the sharp-edged shoulder of the cone-cylinder model is rounded off, however, the expansion waves will be distributed over a larger area and, consequently, the matching problem can be expected to be less severe. To determine the degree of the expected improvement, the flow fields around a cone-ogive-cylinder model with a rounded shoulder and a smoothly curved model, the NACA RM-10 model, were calculated theoretically to obtain, as before, the flow-disturbance characteristics along an ideal wind-tunnel wall. The results of these calculations (see Ref. 2) are presented in Fig. 11.

The rounding of the shoulder of the cone-cylinder model extended over a region equal to approximately one-third of the cone length (see Fig. 11). Even this relatively slight rounding of the shoulder resulted in a considerable reduction of the flow disturbances in the plane of the wall with respect to both pressure and flow inclination. In particular, the magnitude of the maximum inflow angle was reduced to nearly one-third of the corresponding cone-cylinder value. On the other hand, the maximum outflow angle was reduced only slightly. The resulting disturbance characteristics of the cone-ogive model are considerably closer to the characteristics of an ideal perforated test section than are those of the cone-cylinder model. In the extreme case of the continuously-curved NACA RM-10 contour, the mismatch between model disturbances and flow characteristics is reduced to an even greater extent.

A comparison of the characteristic curves of the three models investigated (Fig. 11), shows that for all three contours the same perforated wall can satisfy, to a good approximation, the requirements for matching in the compression-wave region. In the inflow region that is, in the region of negative values for θ_w, a differential-resistance type wall will improve considerably the matching between wall characteristics and model disturbances, as discussed in the previous section and as shown in Fig. 11. This is not entirely true for the RM-10 model with continuous curvature, however, since the improvement in matching is restricted only to the upstream part of the inflow region. In the downstream part of this region the matching is actually better with the ideal perforated wall. Fortunately, in this case the downstream region of mismatch is not serious and will cause no interference on the model since the shock waves reflected from the wall in this region do not intersect the model but pass behind it (see reflection limit in Fig. 11)

Consequently, it may also be said for the continuously-curved RM-10 model that a suitable differential-resistance type wall would reduce wall-interference effects as compared with a conventional perforated wall.

In summarizing the theoretical results for the disturbance characteristics of various contours, it was shown that with conventional perforated walls the elimination of wave reflections from the wind-tunnel wall becomes particularly difficult when a system of concentrated expansion waves exists around parts of models with sharp corners or small radii of curvature. Gradually curved contours with a wide spreading of the expansion-wave system can be expected to produce less severe wave-reflection problems. For all three-dimensional contours, however, conventional perforated or differential-resistance type perforated walls cannot match the required wall characteristics in those regions where outflow from the test section is required in spite of the fact that the static pressure in the test section is lower than that in the surrounding plenum chamber. On the other hand, replacing a conventional perforated wall by a suitable perforated differential-resistance type wall will improve considerably the potential for obtaining interference-free data in wind-tunnel tests for all three-dimensional contours investigated.

V. COMPARISON BETWEEN THE BASIC CHARACTERISTICS OF PERFORATED AND SLOTTED WALLS

A. PERFORATED WALLS

It was stated in the preceding paragraph that a perforated wall of either the conventional or differential-resistance type cannot match the conditions for wave cancellation at the tunnel wall in regions in which outflow is required and when the test-section pressure is lower than the plenum-chamber pressure. This difficulty also exists for a number of other problems associated with testing in perforated test sections. Consider, for example, the subsonic flow around a two-dimensional cylinder in a perforated-wall wind tunnel, as shown in Fig. 12a. The linearized boundary condition for perforated walls (Ref. 12):

$$\Delta v_x + K \cdot \Delta v_n = 0 \qquad \text{(1a)}$$

or:

$$\frac{\Delta p}{q} = 4 \cdot F \cdot \theta_w \qquad \text{(1b)}$$

requires that the flow be directed into the test section in the region of negative disturbance pressures; that is, $\Delta v_x > 0$. For the correct flow conditions, however, the flow upstream from the maximum thickness must be directed outward from the tunnel, and that downstream of the maximum thickness, inward into the tunnel. Consequently, the perforated wall causes basic distortions of the flow pattern as calculated, for instance, by Kassner (Ref. 13) and presented in Fig. 12b according to his results. This characteristic is known to represent a basic deficiency of perforated wind-tunnel walls for subsonic testing. Because the magnitude of this distortion is generally small, however, perforated-wall tunnels have been found satisfactory for use in subsonic testing.

It should be mentioned that the direct application of the theoretical results obtained by Kassner and Goodman (Refs. 12, 13) is complicated because their theory is based upon the assumption of constant entropy for the flow into and out of the test section. In acutal flow, the entropy of the inflow is considerably increased because the axial momentum of the test-section flow entering the plenum chamber is practically lost due to mixing with the stagnant plenum-chamber air. Experiments show (see for example Fig. 18, curve for straight holes) that the increase of entropy causes more air to be sucked into the test section at a given pressure difference than would be the case with constant entropy. However, due to the intense mixing of the test-section stream with the inflow air, the effective displacement of the inflowing air and its effect on the model is essentially reduced. No detailed quantitative theory is available at the present time to calculate theoretically the two opposing effects.

B. SLOTTED WALLS

The boundary conditions for a longitudinally-slotted wall are completely different from those for the perforated wall. In addition to the pressure change caused by the cross-flow velocity component through the slotted wall, an additional pressure difference exists which is dependent upon the curvature of the flow approaching the slotted wall. The pressure change due to the cross-flow component can be represented by:

$$\Delta p/q = K_1 \cdot \theta_w + K_2 \cdot \theta_w^2 \tag{2}$$

where: $K_2 = -\frac{1}{c^2} = \text{constant.}$

In the above equation the linear term corresponds to the friction losses and the quadratic term to the isentropic acceleration of the flow in the slots. The additional term for the pressure change due to curvature of the approaching flow can be expressed in the following form where only linear terms are considered:

$$\frac{\Delta p}{q} = \frac{2}{\pi} \cdot \left[\log\left(\sin\frac{c\pi}{2}\right) - \left(1 - \log 2\right) + \frac{2}{3} \cdot \frac{1}{6} \cdot \left(c\,\frac{\pi}{2}\right)^2 + \frac{4}{5} \cdot \frac{1}{180} \cdot \left(c \cdot \frac{\pi}{2}\right)^4\right] \cdot \frac{\partial\theta_w}{\partial x/h}$$

$$= -\frac{2}{\pi} \cdot \log\left(\sin\frac{c\pi}{2}\right) \cdot \frac{\partial\theta_w}{\partial x/h} \qquad (3)$$

where: $\frac{\partial\theta_w}{\partial x}$ = flow curvature in flow direction.

The derivation of Equation 3, given in Ref. 14, is based on Guderley's theoretical investigations for interference effects in slotted wind tunnels (see Ref. 15). For non-viscous flow in the vicinity of a slotted wall, Equation 3 represents the only pressure drop term within the validity of the linearized theory since the other terms of Equation 2 will then vanish. The above equation may be applied for subsonic as well as supersonic flow within the validity of the linearized theory (Refs. 14, 16, 17).

The additional pressure difference due to flow curvature near slotted walls (Equation 3) is caused by centrifugal forces which are magnified by the slot effect. An analogous magnification may be observed in open-jet tunnels. This is illustrated in Figs. 13a and 13b. In subsonic free-flight (Fig. 13a), equilibrium between the pressure on the surface of the model and that in the undisturbed flow is attained through centrifugal forces extending throughout the entire flow field, that is, to infinity. In the open-jet tunnel (Fig. 13b), however, this equilibrium must be achieved within a finite distance, namely in the region between the model and the boundary of the jet. To accomplish this, the curvature of the flow in the open-jet must be increased above that for free-flight, and a corresponding increase or magnification of centrifugal forces results. In the case of a model in a slotted-wall wind tunnel, the centrifugal forces for the streamlines in the vicinity of the wall are increased because of the open-jet effect in the slot area. Consequently, an additional mean pressure buildup occurs in the vicinity of the mixed tunnel wall, the magnitude of which is given by Equation 3. The increased streamline curvature along slotted walls is shown schematically in some detail in Fig. 14a.

The significance of the curvature effect upon the pressure drop across the wall lies in the fact that for sufficiently large curvature this effect may be predominant. When this is the case, a slotted wall can support a cross-flow in a direction opposite that indicated by the difference between test-section and plenum-chamber pressures. Since, as

discussed previously, a wall with such characteristics is required for the cancellation of expansion waves emanating from the shoulders of a cone-cylinder model, the slotted wall, for example, offers some significant potentiality for this purpose.

From Equation 3 it may be seen that the additional pressure buildup occurring in curved flow approaching a slotted wall is directly proportional to the distance between slot centers. This fact is readily understood when it is realized that, for a given open-area ratio of the walls, the radial extent of the high-curvature region near the walls is proportional to the distance between slots (see Fig. 14b).[1] Since, for a constant open-area ratio, the relative distribution of the normal velocities over each slot and slot region must be independent of the number of the slots, the streamline curvatures and the centrifugal forces per unit mass flow of air at corresponding points are also independent of slot number. Consequently, the total pressure buildup in the high-curvature region must be proportional to the radial extent of the high-curvature region or, as stated before, to the distance between slot centers. Thus, to maintain a desired constant value of the additional pressure buildup but with a greater number of slots, it is necessary to reduce the slot width and compensate for the smaller thickness of the high-curvature region by increasing the curvature of the flow in the slot region.

The theoretical treatment, as discussed above, assumes that at the root of the slots (see Figs. 14b and 14c) the static pressure is equal to the undisturbed pressure of the flow, that is, to the plenum-chamber pressure. This is, of course, not exactly true since the flow will extend beyond the wall openings and produce centrifugal forces. Hence, the static pressure at the root of the slots will be different from the plenum-chamber pressure since this pressure must correspond to that of the outer streamline. In the case of slots without lateral guiding surfaces, the error introduced by this assumption can be expected to be relatively small, as has been found true in the case of the open-jet tunnel. In the case of slots with lateral guiding surfaces, however, the slot channels will be partially filled with flow of high curvature so that the effect of the centrifugal forces occurring outside the inner wall boundary will be larger than in the case of the slots without lateral

1. There exists, of course, a purely geometrical relationship between number of slots, distance between slots, slot width, and open-area ratio. Thus for a given constant open-area ratio, decreasing the distance between slots (assuming a uniform distribution circumferentially) implies a greater number of slots and a reduced slot width.

guiding surfaces. Even in this case, however, the filling effect of the slots can be shown to be of second order since flow curvature as well as filling of the slots depends upon the relative size of the model in a given wind tunnel, that is:

$$\text{Flow curvature:} \qquad \partial\theta_w/\partial x = \sim \mathrm{Vol}/H^3$$

$$\text{Relative filling of slot:} \quad \Delta l/H = \sim \mathrm{Vol}/H^3$$

and, finally, the pressure buildup in the slots:

$$\Delta p_{slot}/q = \sim (\mathrm{Vol}/H^3)^2 \, . \tag{4}$$

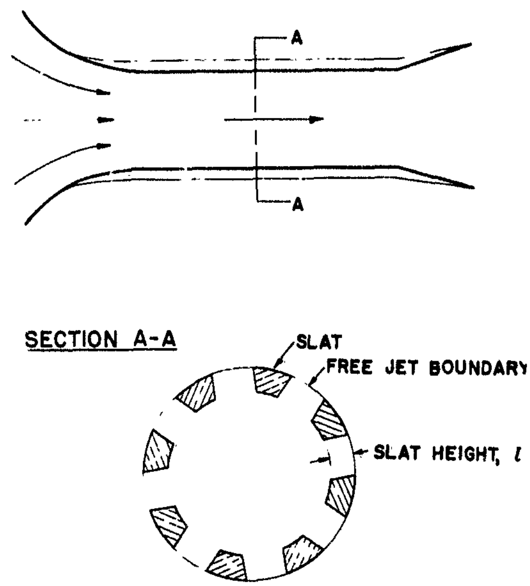
The net effect of the flow outside of the slots is to increase the resistance of the tunnel wall to cross-flow; that is, a given difference between the pressures in test section and plenum chamber will be produced by slots wider than would be predicted by theory.

There is another difference between the theoretical and the actual flow in the vicinity of slotted walls. This is created by the assumption that, as in the theory for perforated walls, the flow from the plenum chamber into the test section has the same entropy as the flow in the tunnel. However, as explained previously in the case of perforated walls, the inflow will have lost a great part of its axial momentum; thus the centrifugal forces of the inflow will be considerably reduced in comparison with the theoretical values. It must be expected, therefore, that in the inflow region of slotted walls a symmetrical flow field will be produced, as in perforated test sections.

C. SLOTTED WALLS WITH PROTRUDING SLATS

Another interesting slotted test-section configuration that has been studied theoretically deserves mention. This configuration has the solid wall portions (slats) protruding into the test section, and the slots are equipped with solid or perforated sidewalls for guiding the flow (Sketch 1). It has been informally reported that a Swedish transonic wind tunnel has walls of this type. In such a test section, centrifugal pressure gradients are amplified in the slot flow when the approaching flow is curved. In Ref. 14, it is shown that the total pressure buildup of a slotted wall with protruding slats is:

$$(\Delta p/q)_{slot} = \frac{\partial\,\theta_w}{\partial(x/h)} \cdot \left[\frac{2}{\pi} \cdot \log\left(\sin\frac{c\pi}{2}\right) - \frac{2}{c} \cdot \frac{l}{h} \right] .$$



Sketch 1. Slotted Test Section with Protruding Slats.

Since the pressure buildup across a wall of this type is increased by increasing the slat height, the slots in such a wall must be made wider if their effectiveness is not to be changed.

It might also be noticed that the boundary conditions for this configuration may be realized by a configuration in which the lateral guides of the slots are made to protrude into the flow. Since these guides can be made adjustable, and possibly controllable, it appears possible to develop a wall with characteristics that can be varied to conform to imposed test conditions.

The choice of a wall configuration for a transonic tunnel involves a compromise between the pressure-equilibrium conditions and those required for effective shock cancellation. The additional parameter, the slot height, strengthens the possibility for attaining a satisfactory compromise. This extra degree of freedom makes this configuration quite attractive since the conventional-type slotted walls do not possess this flexibility.

As shown in preceding discussions, a slotted wall can support outflow from the test section even in cases when the pressure inside of the test section is less than the pressure in the plenum chamber. Therefore, it can be expected that a slotted test section can eliminate some of the difficulties which occur in perforated-wall test sections in the region where expansion waves impinge on the test-section walls.

D. VARIOUS BODIES OF REVOLUTION IN A COMBINED PERFORATED-SLOTTED TEST SECTION

As pointed out in Section III, B, it is possible to produce a perforated-slotted test section which combines the characteristics of both the perforated and the slotted test section by covering the openings of a slotted test section with perforated cover sheets. To determine whether or not this configuration has promise, a theoretical investigation of the flow around several three-dimensional bodies in test sections of the combined type was conducted. Again, required theoretical data for the bodies in free-flight were taken from Ref. 2.

The flow around the model was calculated for the plane corresponding to the tunnel wall (see Fig. 11). To the pressure occurring in free-flight was added the pressure which can be supported by a longitudinally-slotted wall from Equation 3. The resulting disturbance pressure is that which must be supported by the perforated cover plates. Since perforated walls have essentially linear characteristics, a satisfactory match can be obtained if the resulting disturbance pressure curve is also linear.

The results of the calculation for the cone-cylinder model with 2-percent blockage in a test section having 16 longitudinal slots and an open area of 36 percent are presented in Fig. 15. From Equation 3, it can be seen that approximately the same results will be attained with walls which have 32 or 64 slots with open areas of 18 percent and 5 percent, respectively. For the purpose of these calculations, the regions with abrupt changes of pressure (see Fig. 10, points A, B and C) were smoothed out over a length corresponding to the distance between the wall slots. It is apparent in Fig. 15 that the slot effect considerably reduces the difficulty previously noted with respect to the support of negative pressures inside the tunnel in outflow regions. It may also be noted that the characteristics of the remaining wall-pressure disturbances match fairly well the characteristics of an ideal perforated wall in the entire region of the initial compression and the initial expansion waves. In the region behind the expansion-wave system, however, significant differences between the desired characteristics and the ideal perforated-wall characteristics still exist. These remaining differences can be reduced considerably by means of properly matched differential-resistance cover plates as discussed in Section II (see Fig. 11).

The slot effect on the disturbance-flow characteristics of the continuously-curved NACA RM-10 model was also investigated for the wall configurations with 16 and 8 slots, both with 5-percent open areas. The

results (presented in Fig. 16) indicate that with suitably combined perforated-slotted walls, the disturbance pressures of this model at the tunnel wall can be satisfactorily matched. In order to make the matching perfect for the case of the RM-10 model, it would be necessary either to reduce the total open area to 2.2 percent with 16 slots or to keep the open area of 5 percent and reduce the number of slots to approximately eleven, as follows from Equation 3.

Summarizing the theoretical results for combined perforated-slotted walls, it can be concluded that such a combination wall offers substantial promise for the testing of smoothly-curved models. Shock reflection difficulties, however, may be expected when tests are conducted in such a test section with models having regions of strong compression waves since a large portion of the test-section walls must be solid.

VI. DEVELOPMENT OF A DIFFERENTIAL-RESISTANCE WALL

In Section IV, the desirability of having a wind-tunnel wall with different characteristics for outflow and inflow was discussed. In order to ascertain the possibility of fabricating such a wall, Chew's experimental studies in the TMT on wall characteristics (see Ref. 18) were extended to include some special walls which were expected to throttle inflow more effectively than outflow (Ref. 3).[2]

It should be mentioned that in 1950 an investigation conducted by McLafferty and Schweiger of United Aircraft Corporation dealt with a similar problem in connection with the performance of supersonic engine inlets (Ref. 19). In this investigation, the so-called "educated" hole was studied which, as predicted by supersonic flow theory, prevented outflow through the holes in spite of a favorable pressure difference. The basic design features of an "educated" hole in comparison with the conventional hole are presented in Fig. 17 from the UAC report. In the case of the "educated" hole, outflow is prevented by suitable shaping of the downstream edge of the hole.

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2. The investigations of the wall-characteristic tests were presented for a Mach number of 0.90 instead of the desired Mach number 1.20. The Transonic Model Tunnel was not equipped with a flexible nozzle at the time of the tests so that, in the supersonic range, the flow had to be established by means of plenum chamber suction. Consequently, the wall characteristics could be more precisely determined in the subsonic range.

The "educated" hole, however, operates with a pressure difference of opposite sign to that required for the differential-resistance wall for wind-tunnel testing. Although the "educated" hole prevents outflow from a high-pressure flow region into a surrounding chamber with lower pressure, the desired differential-resistance type wall must throttle the inflow from the plenum chamber into the low-pressure test-section flow. Hence, it is obvious that the principle of the "educated" hole cannot apply to the transonic testing problem.

The guiding idea utilized for the development of a differential-resistance wall is as follows. It is obvious that the resistance to inflow could be increased if the inflow could be directed against the main test-section flow. The inflowing air would then have to overcome at least a part of the dynamic pressure of the test-section flow. This end can be attained rather simply by merely inclining the holes in a sufficiently thick perforated wall to oblique angles against the main flow direction. Walls of this type have been previously investigated in the outflow region by United Aircraft Corporation (see Ref. 20). It was found in these tests that the resistance of a perforated wall to outflow from a test section can be significantly reduced by inclining the holes in the direction of outflow. This characteristic matches very well the wall characteristics required for testing of three-dimensional models since, with the use of inclined holes, the number of holes in the walls could be reduced for a desired outflow resistance; whereas, on the other hand, reducing the number of holes would increase the resistance of the wall toward inflow.

Some typical results of Chew's tests of walls with holes inclined at various angles are shown in Fig. 18. It will be noted that by inclining the holes from $\alpha = 0^{o}$ (that is, normal to flow direction) to 45^{o} and 60^{o}, the outflow resistance of the wall is considerably reduced. Simultaneously, the resistance to inflow is gradually increased with angle of inclination, particularly in the case of the holes inclined 60^{o}. In view of the favorable relative magnitude of inflow and outflow resistance, further studies were concentrated on the 60^{o} inclined-hole wall. The number of holes was subsequently reduced to one-half of the initial number (see Fig. 19a), and a characteristic was obtained for a 6-percent open-area wall, which in the outflow region matches reasonably well the characteristics of a conventional perforated wall with 22-percent open area. (Note that according to Fig. 2 the latter wall produced good results in the compression-wave region.)

When a specific wall geometry with a given cross-flow characteristic is selected, the reference point for the empty test section can be shifted along the characteristic curve by changing the wall alignment

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VII. CONE-CYLINDER INVESTIGATIONS IN DIFFERENTIAL-RESISTANCE TYPE TEST SECTION

A. PERFORATED TEST SECTIONS

The investigations discussed in the preceding paragraphs indicated that the differential-type perforated test section developed as a result of Chew's tests would be capable of overcoming a major portion of the difficulties encountered in the testing of cone-cylinder models in conventional perforated or slotted test sections. Consequently, a series of investigations were initiated to verify the improved testing characteristics of these differential-resistance type wind-tunnel walls with 60^{o} inclined holes and 6-percent nominal open-area ratio. Some typical test results (Ref. 1) for the cone-cylinder model with 2-percent blockage obtained by Gray and Gardenier in the TMT with this new test section are presented in Fig. 20. It can readily be seen that the experimental test data follow closely the theoretical curve. The differences observed are of a magnitude of no more than 1 percent to 1-1/2 percent of the total pressure, which, to some extent, may be explained by the non-uniformity of the empty test-section flow. The improvement in the test results for the differential-resistance type wall are obvious when they are compared with the data obtained with either the conventional perforated or slotted test section (see Figs. 2 and 7). Reflected waves are considerably reduced not only in the compression-wave region but also in the expansion-wave region.

Although smoothly curved models should be less critical than cone-cylinder contours, there is a need for further investigation to determine whether the same good results obtained with the new type wall can also be obtained with models not having the extreme shape of the cone-cylinder. More detailed investigations of other model shapes and of other Mach numbers are being prepared and will be carried out in the near future.

B. SLOTTED TEST SECTIONS WITH PERFORATED COVER PLATES

As is indicated in Fig. 9c, compression-wave cancellation for a cone-cylinder model could be accomplished fairly well in a combination slotted-perforated test section, whereas in the expansion-wave region strong wave reflections occurred which are like those on an open-jet boundary. For this reason, differential-type cover plates over the slots should be beneficial, as was true in the case of the conventional perforated test section. It is also to be noted that for the slot open area of 53 percent employed in the configuration of Fig. 9c, the basic

advantage of a slotted test section, with respect to the amplifications of the streamline curvature, is utilized insufficiently (see Equation 3 and Fig. 15).

In another series of tests, therefore, an attempt was made to fabricate test-section walls with differential-resistance type cover plates of such a low outflow resistance that the slot open-area ratio could be kept small enough to produce a noticeable slot over-curvature effect. In this test series, the longitudinal slots were covered by plates with holes inclined at 60° angles and with an open area of 22 percent. Typical TMT test results for such a wall configuration with 12 slots and a slot open area of 20 percent are presented in Fig. 21. For the selected slot configuration, the experimental results with differential-resistance cover plates coincide much better with theory than the results obtained with conventional slots. It should be noted that the test Mach number was obviously somewhat smaller than the Mach number 1.20 of the theory, as is indicated by the generally too high pressure along the model surface (see Fig. 21). In spite of this discrepancy it can be seen that the compression waves as well as the expansion waves produce wall-interference disturbances of no more than 3 percent of the total pressure. These disturbances, however, are considerably larger than those in perforated test sections of the differential-resistance type. It should be noted that, for the number of slots and the open-area ratio employed, a favorable slot curvature effect can be expected with a magnitude of approximately two and one-half times the values corresponding to the conditions presented previously in Fig. 15.

The tests with combination perforated-slotted walls of the differential-resistance type indicate that it is possible to obtain fairly reliable data for cone-cylinder models in such test sections in the Mach number range around $M = 1.20$. It should be realized, however, that even in this selected three-dimensional case, concentrated shock waves are of small intensity. For example, the initial conical shock produces at the tunnel wall no more than one-fifth of the entire pressure rise. In the case of models which produce strong shock waves, the conditions with respect to wave cancellation are more severe. It must be expected, in these cases, that reflections on the large solid-wall portions in between the slots will meet the model before their intensity is sufficiently reduced by the counteracting effect of the slot waves. Further investigations are needed before the potential of such combination slotted-perforated type test sections can be properly defined.

VIII. CONCLUSIONS

Experimental and theoretical investigations of the testing characteristics of various types of transonic test sections provided the following conclusions for three-dimensional model configurations with 2-percent blockage at a Mach number of 1.2:

A. Experimental results from the Transonic Model Tunnel showed that the wave system produced by cone-cylinder models cannot be effectively absorbed by either conventional perforated or slotted test-section walls. In the case of perforated test sections, it is relatively easy to eliminate reflections of the initial conical shock and the subsequent compression-wave system by suitable selection of the wall geometry; however, the concentrated expansion-wave system originating at the shoulder of the model is strongly reflected by such a wall. On the other hand, it is also possible to devise a perforated wall with a geometry such that the conditions of no-reflection for the expansion waves are satisfied; however, in this case the preceding compression wave system is strongly reflected by the wall.

B. Theoretical investigations verified and extended the experimental knowledge on the origin of the observed difficulties for a three-dimensional wave system. Theory confirmed that a conventional perforated wall with constant geometry is incapable of simultaneously eliminating wave reflections in the entire compression- and expansion-wave regions since different wall characteristics are required for the different regions. The greatest discrepancies between the required and the actual wall characteristics of a perforated wall have been traced to the region where the three-dimensional expansion-wave system requires continued outflow from the test section while the static pressure in the test section is lower than the plenum-chamber pressure. It was shown theoretically that a wall with different resistance characteristics for outflow and inflow would match more closely the required configuration.

C. Theoretical investigations showed that the mismatch between required and actual characteristics of perforated walls is not restricted to cone-cylinder models but occurs also with models of different contours, such as cone-ogive-cylinder models and the continuously-curved NACA RM-10 model. The observed discrepancies, however, are essentially reduced for models with gradually curved contours which avoid concentration of

expansion waves. Also in the case of smoothly curved contours, such as the RM-10 model, the differential-type wall matches more closely the desired characteristics than does the conventional perforated test section.

D. Theoretical considerations indicated that a perforated wall with a differential resistance to inflow and outflow would produce effective cancellation for both expansion and compression waves.

E. Experimental investigations of wall characteristics showed that a differential-resistance type wall can be fabricated by inclining axes of the holes of a perforated wall into the flow and by selecting a suitable open-area ratio of the wall.

F. Perforated walls of the conventional or differential-resistance type cannot produce characteristics which support outflow of the test section in low pressure regions of the model. Theoretical considerations showed that combined slotted-perforated test-section configurations can be devised which will eliminate effectively this basic difficulty. The required small open-area ratio of such a slotted wall and the required small number of slots makes such a combination wall appear feasible only for model configurations without strong shock waves impinging on the tunnel wall.

G. Tests of a cone-cylinder model with 2-percent blockage in a suitable, perforated test section of the differential-resistance type verified the theory that satisfactorily good results closely matching interference-free data can be obtained in such a test section. Also, suitably selected combination perforated-slotted test sections with the slots covered with plates of the differential-resistance type eliminate severe wave-reflection interferences for the same model.

H. The serious difficulties observed in testing cone-cylinder models in conventional test sections of the perforated and, to a lesser degree, of the slotted type have been solved by the development of perforated as well as combination slotted-perforated walls of the differential-resistance type. The question of which of the two new test-section types will be superior should be investigated for other model configurations. It can be expected that the differential-resistance walls will be superior for model configurations which produce strong shock waves. On the other hand, tests of model configurations with a more continuous wave distribution over the model length can be expected to yield more favorable results in test sections of the combination slotted-perforated type.

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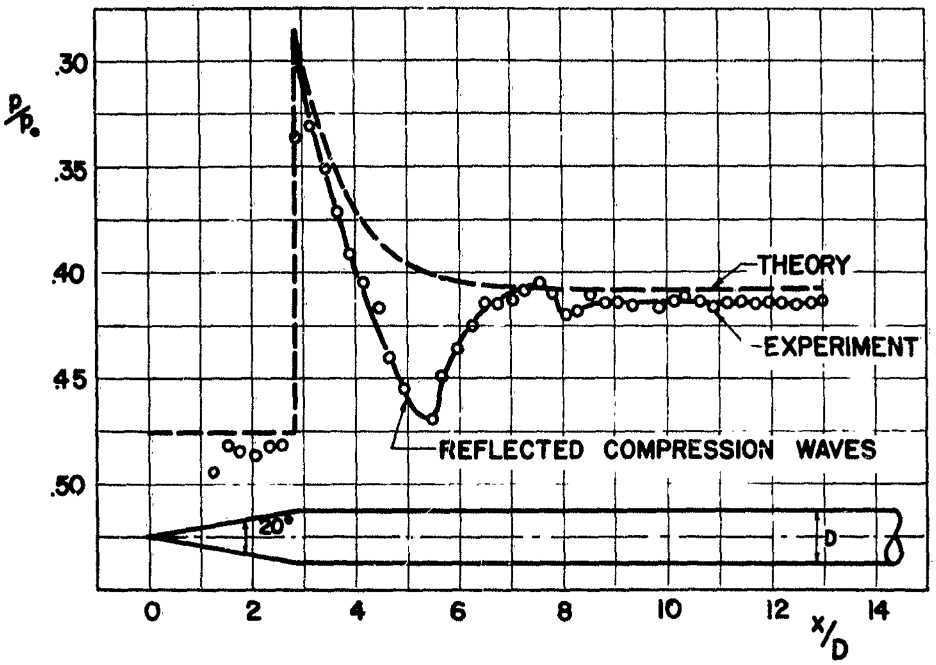


Fig. 1. Pressure Distribution along Surface of Cone-Cylinder Model for Perforated Walls with 12-Percent Open Area, 0' Wall Setting, 2-Percent Blockage--at $M = 1.20$

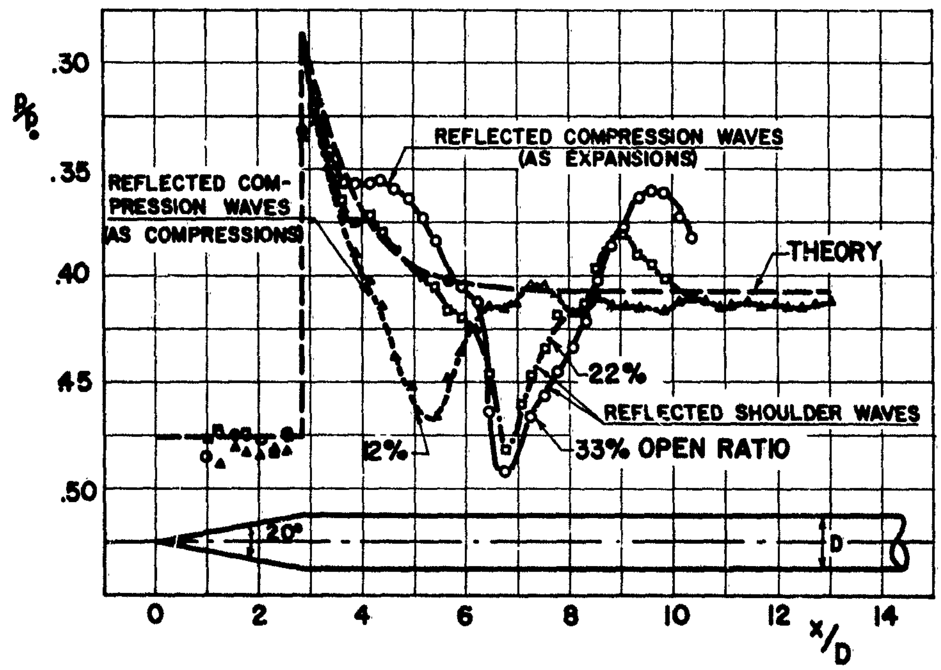


Fig. 2. Pressure Distribution along Surface of Cone-Cylinder Model for Perforated Walls with Different Open-Area Ratios, 0' Wall Setting, 2-Percent Blockage --at $M = 1.20$

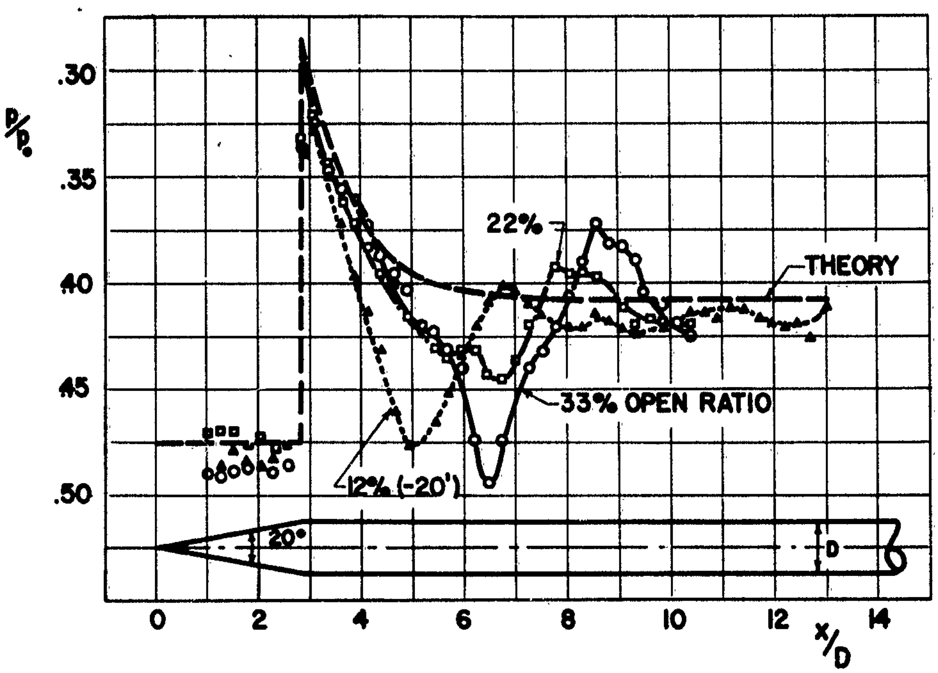


Fig. 3. Pressure Distribution along Surface of Cone-Cylinder Model for Perforated Walls with Different Open-Area Ratios, -20' and -30' Converged Wall Setting, 2-Percent Blockage--at $M = 1.20$

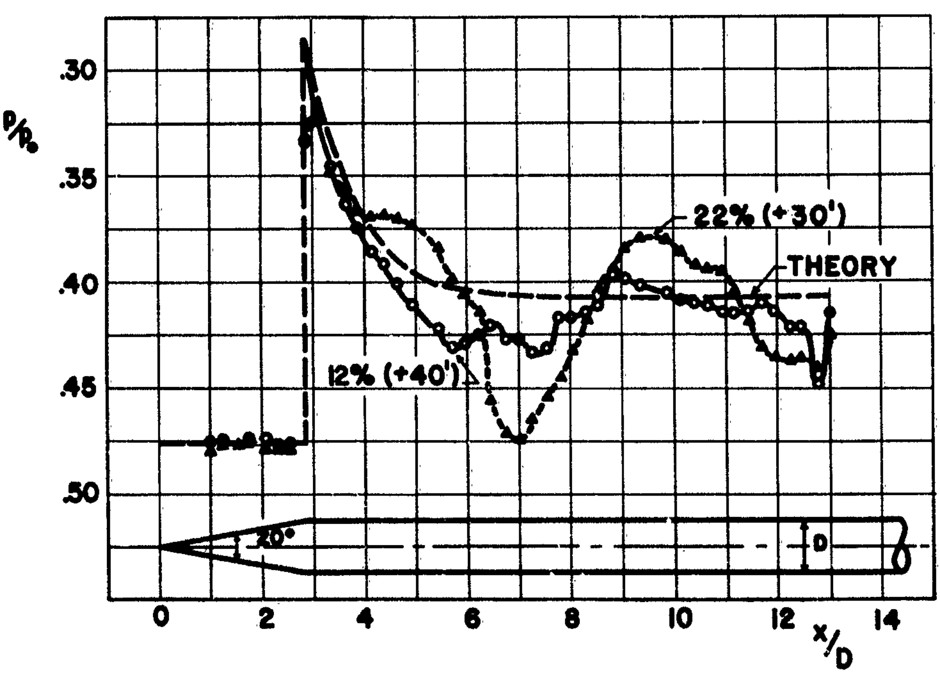


Fig. 4. Pressure Distribution along Surface of Cone-Cylinder Model for Perforated Walls with Different Open-Area Ratios, +30' and +40' Diverged Wall Setting, 2-Percent Blockage-- at $M = 1.20$

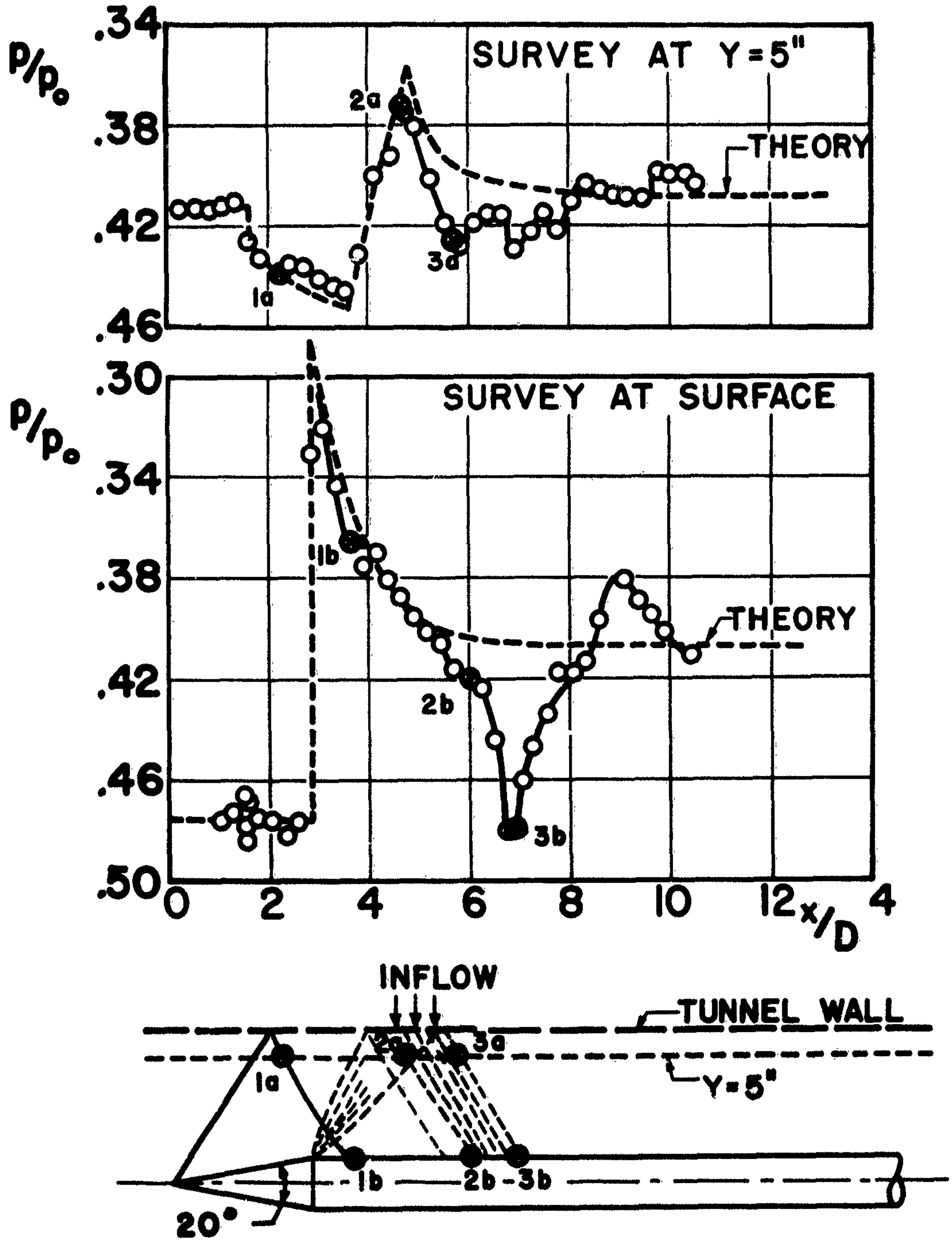


Fig. 5. Wave System and Pressure Survey Results for a Cone-Cylinder Model with 2-Percent Blockage in Conventional Perforated-Wall Test Section with 22-Percent Open Area--at $M = 1.20$

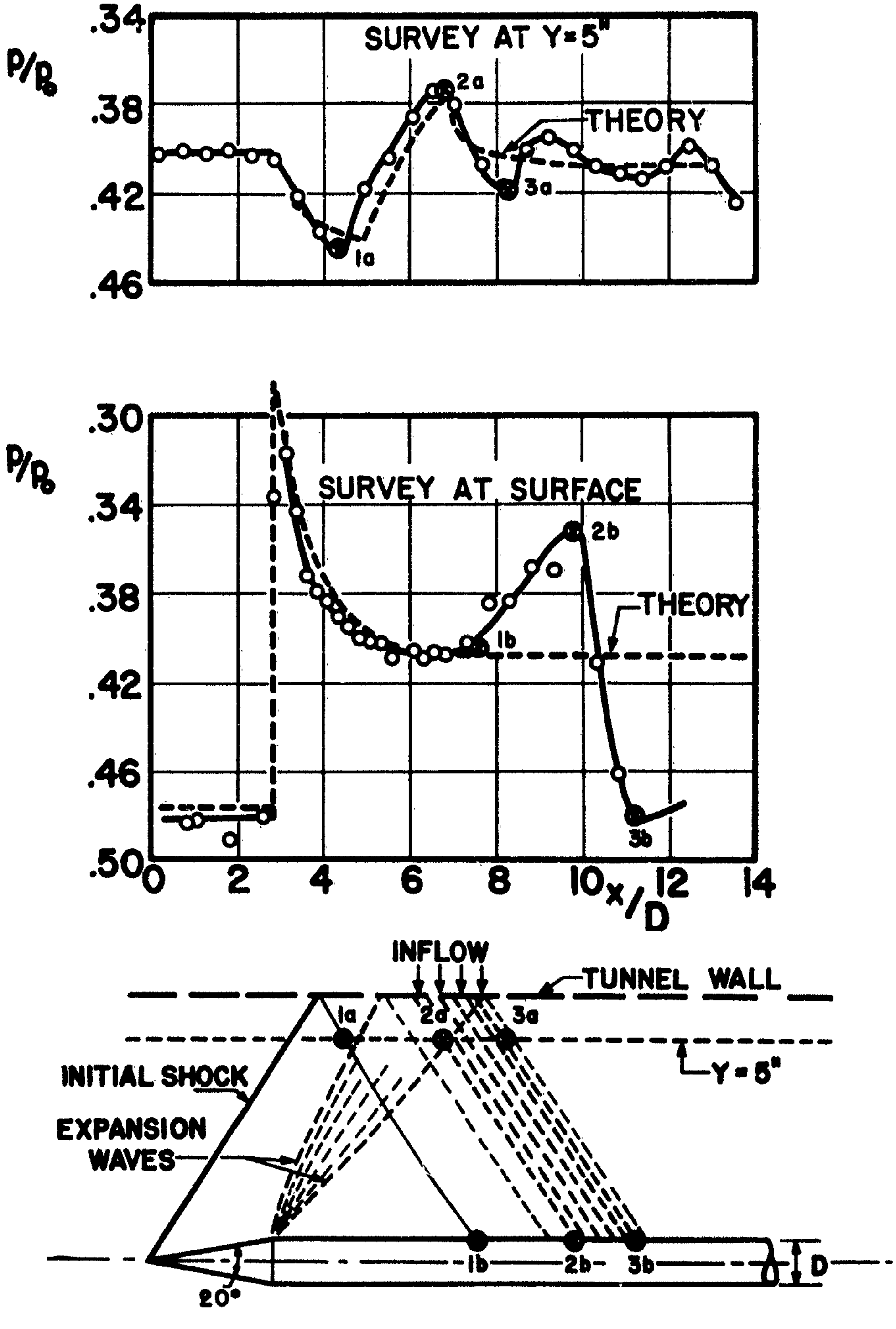


Fig. 6. Wave System and Pressure Survey Results for a Cone-Cylinder Model with ½-Percent Blockage in Conventional Perforated-Wall Test Section with 33-Percent Open Area--at $M = 1.20$

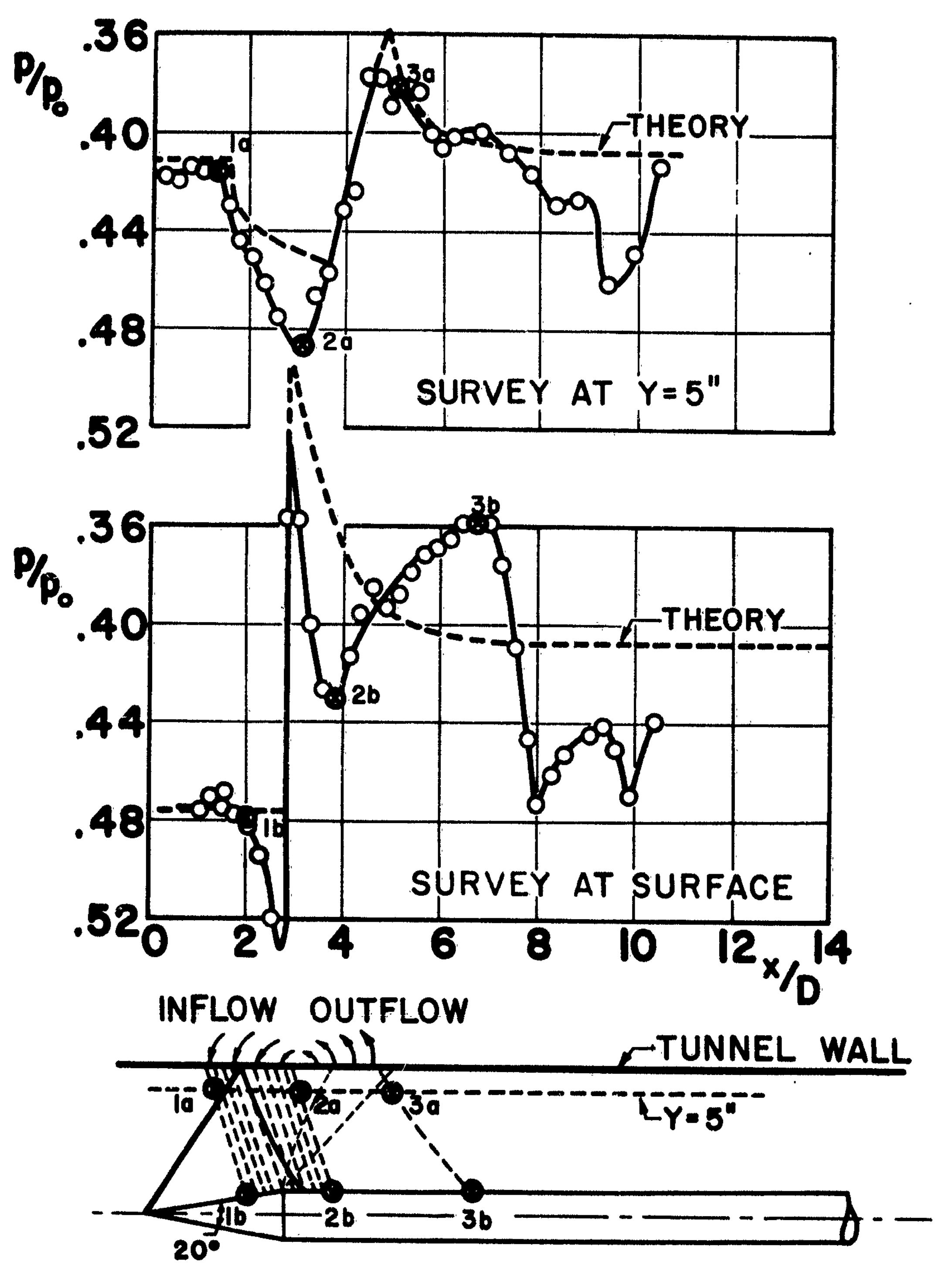


Fig. 7. Wave System and Pressure Survey Results for a Cone-Cylinder Model with 2-Percent Blockage in a Longitudinally-Slotted Test Section--16 Slots in Parallel Walls with 11-Percent Open Area--at $M = 1.20$

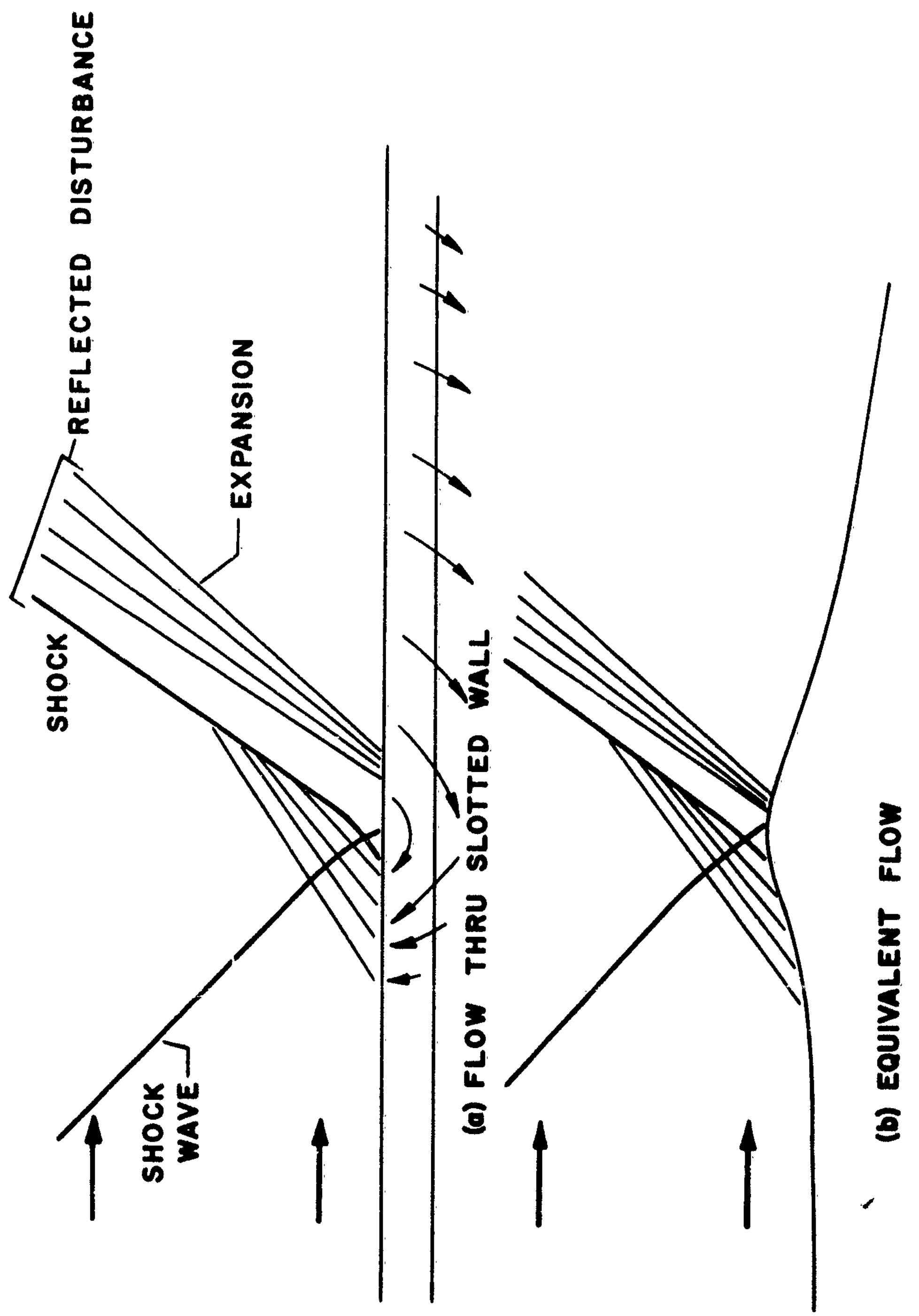
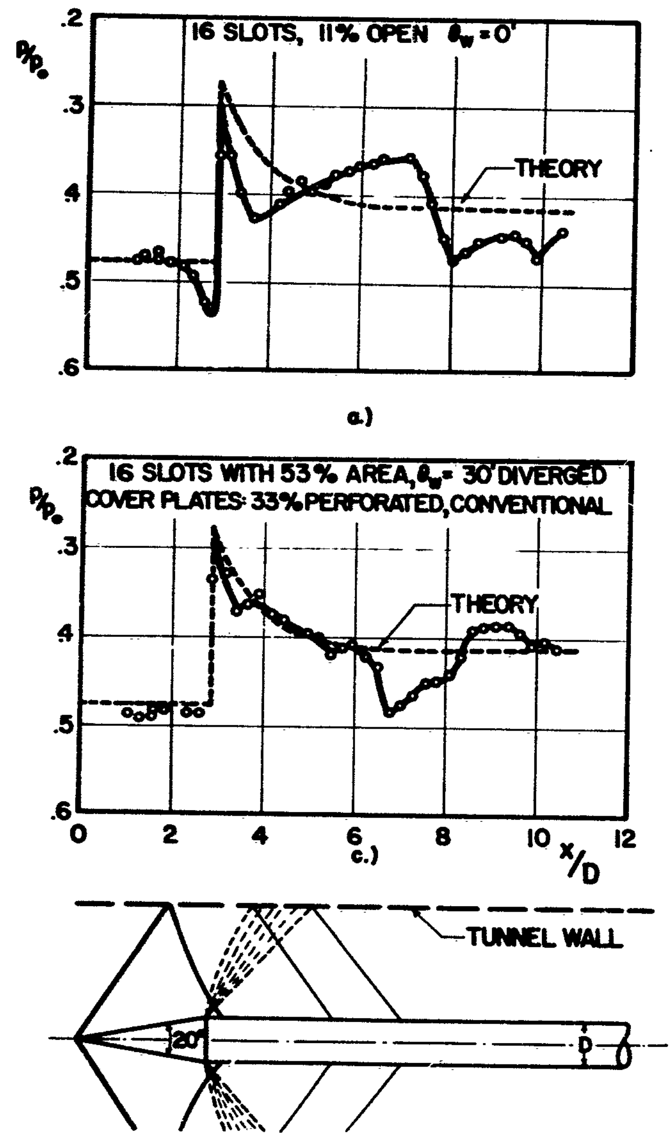


Fig. 8. Secondary Flow Field and Wave System for Shock-Wave Reflection at a Slotted Wall (from Ref. 9)



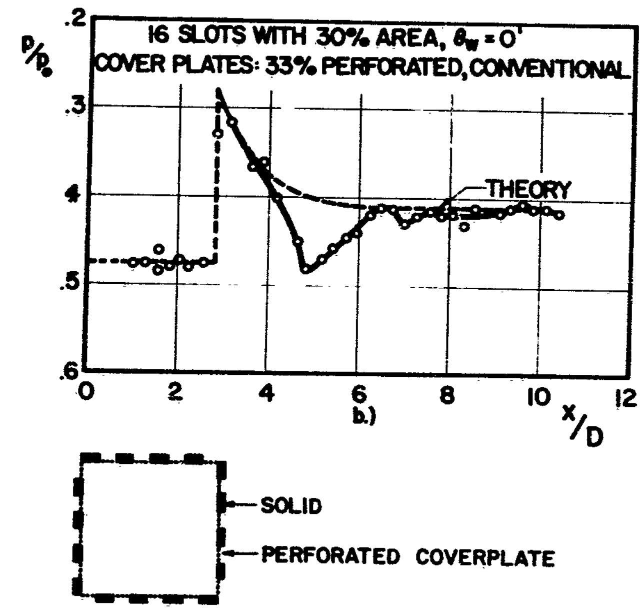


Fig. 9. Pressure Distribution along Surface of Cone-Cylinder Model with 2-Percent Blockage in Various Slotted-Wall Test Sections, with and without Slot Cover Plates--at $M = 1.20$.

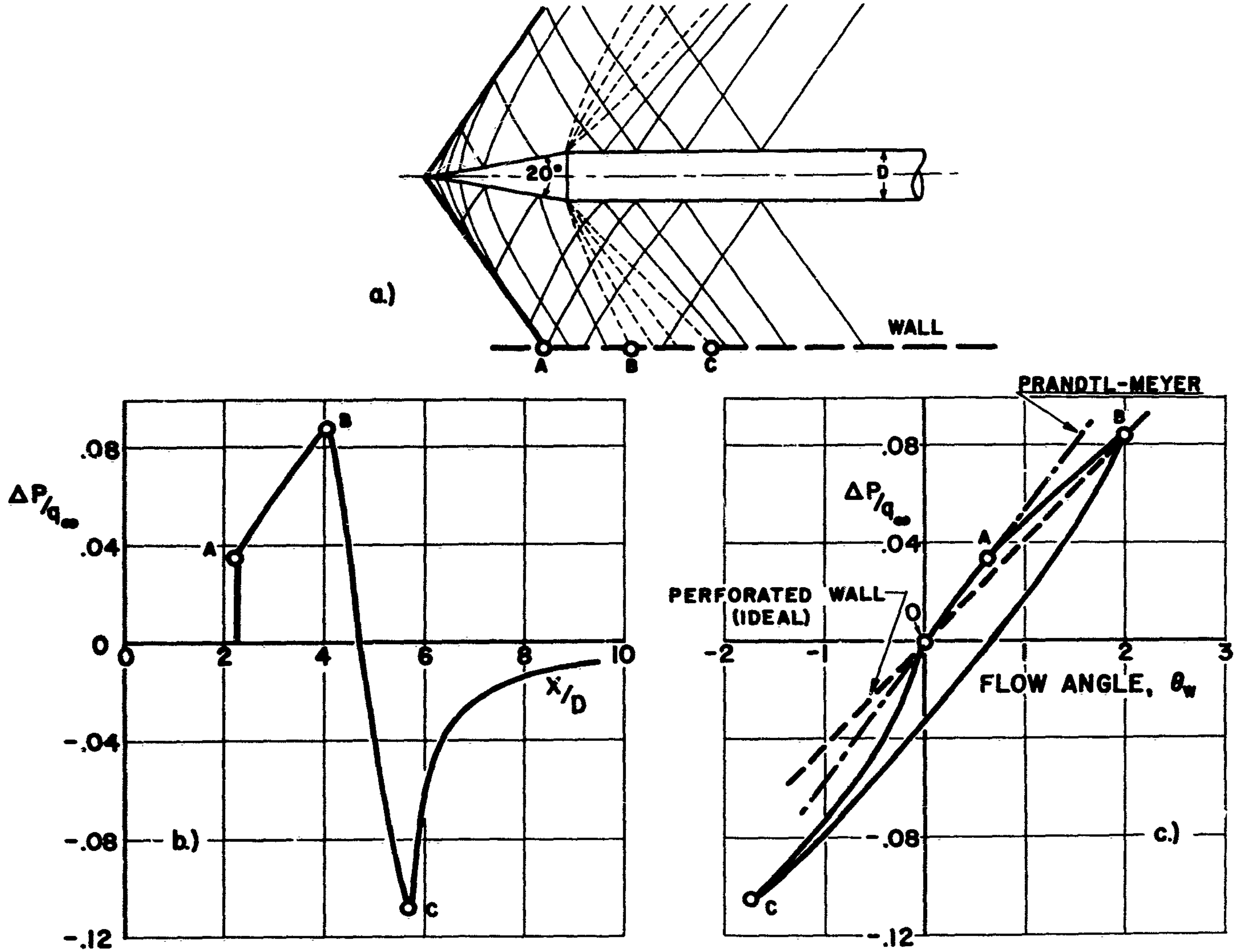


Fig. 10. Theoretical Disturbance Distribution and Wave System of Cone-Cylinder Model with 2-Percent Blockage--at $M = 1.20$

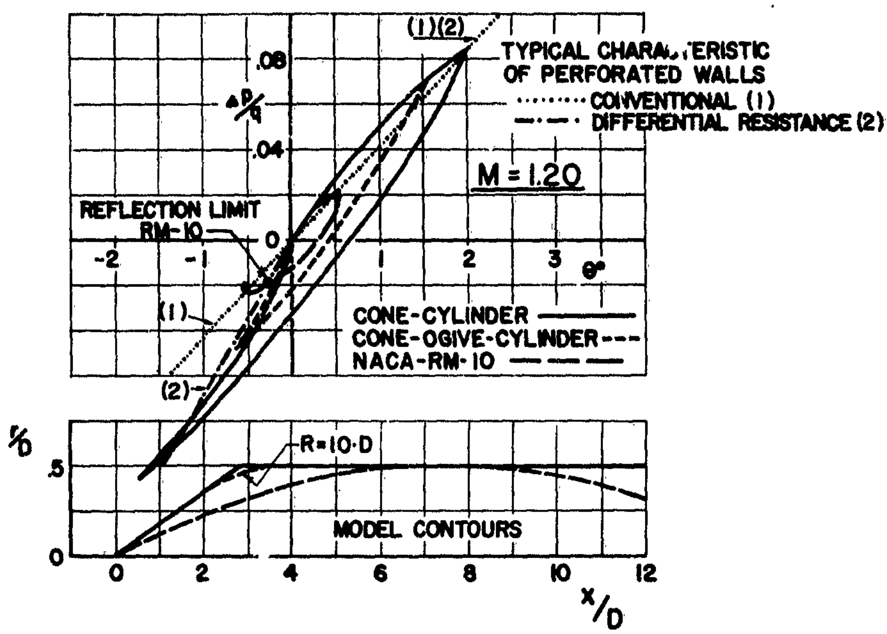


Fig. 11. Theoretical Disturbance Distribution along Test-Section Wall for Several Bodies of Revolution with 2-Percent Blockage--at $M = 1.20$

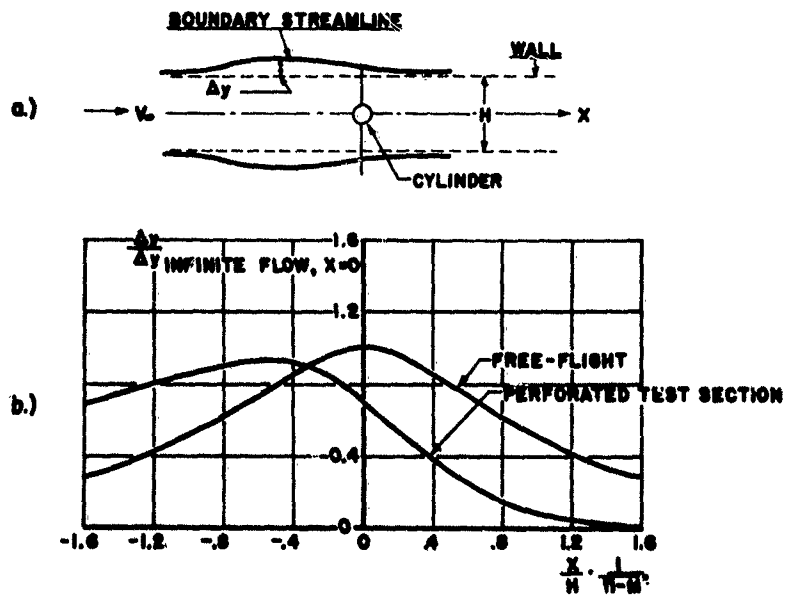


Fig. 12. Calculated Boundary Streamlines for Two-Dimensional Cylinder in Free Flight and in Perforated-Wall Test Section

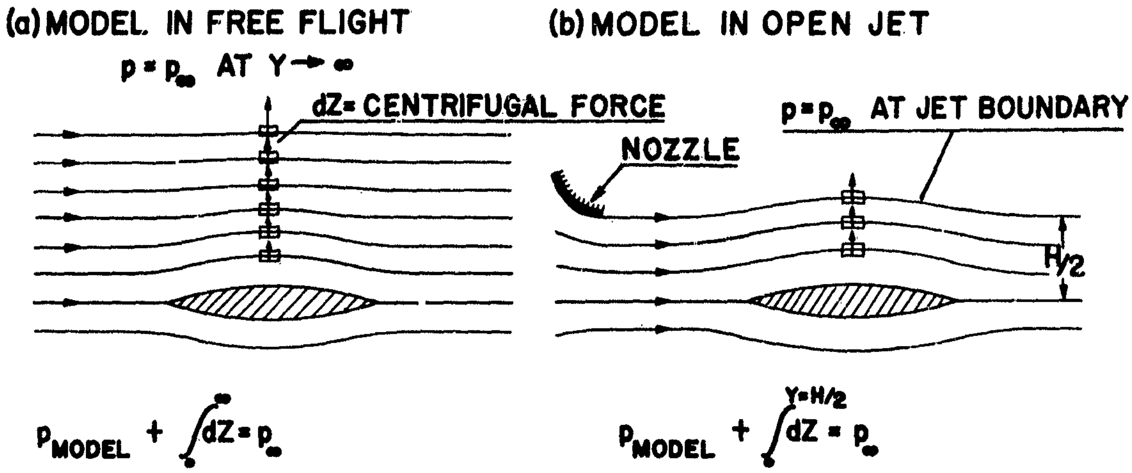


Fig. 13. Pressure Buildup due to Centrifugal Forces in Free Flight and in an Open Jet

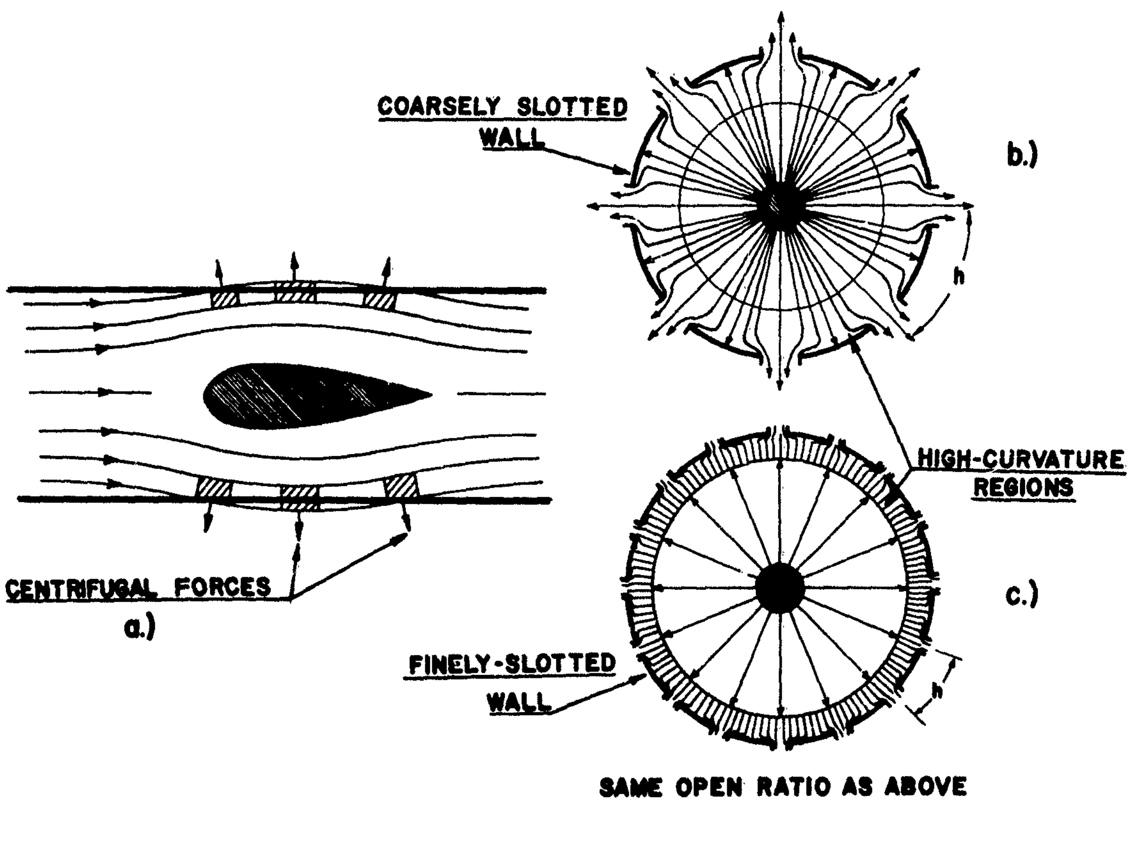


Fig. 14. Flow Pattern in the Vicinity of Slotted Walls

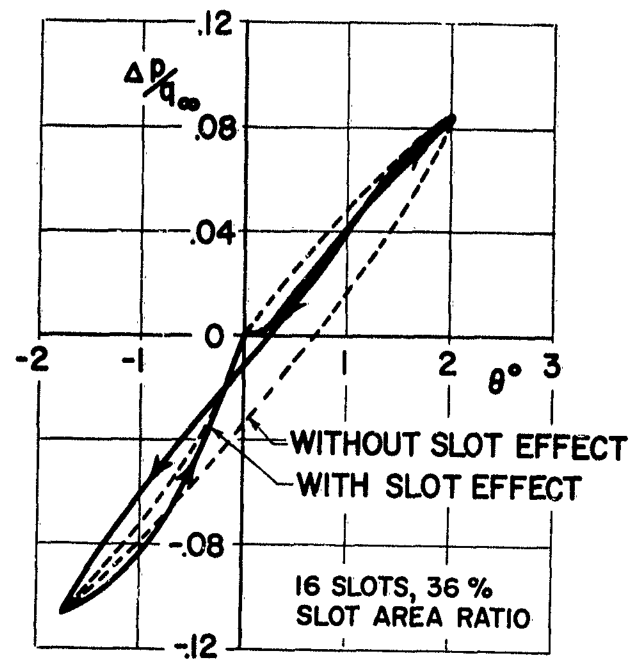


Fig. 15. Flow Disturbances along the Walls of a Test Section with Longitudinal Slots for a Cone-Cylinder Model with 2-Percent Blockage, 20° Cone Angle--at $M = 1.20$

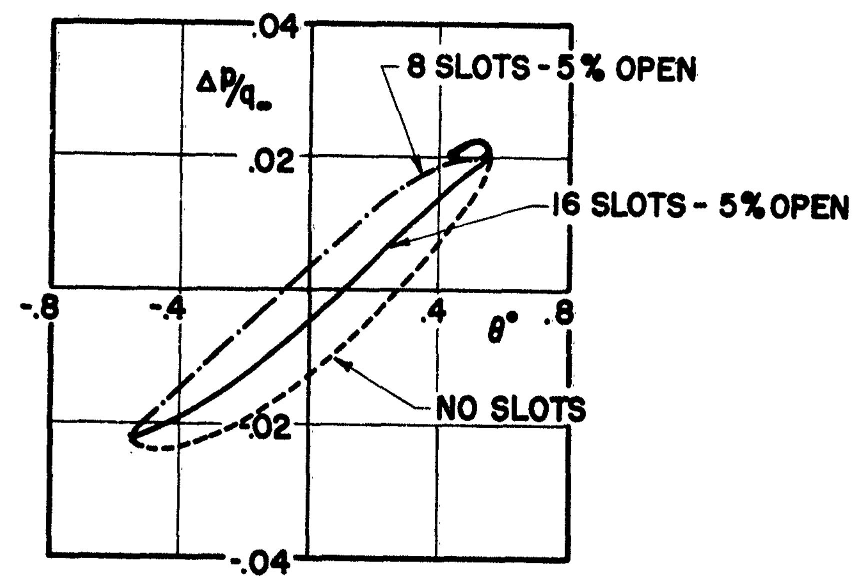


Fig. 16. Flow Disturbances along the Walls of Test Sections with and without Longitudinal Slots for NACA RM-10 Model with 2-Percent Blockage--at $M = 1.20$

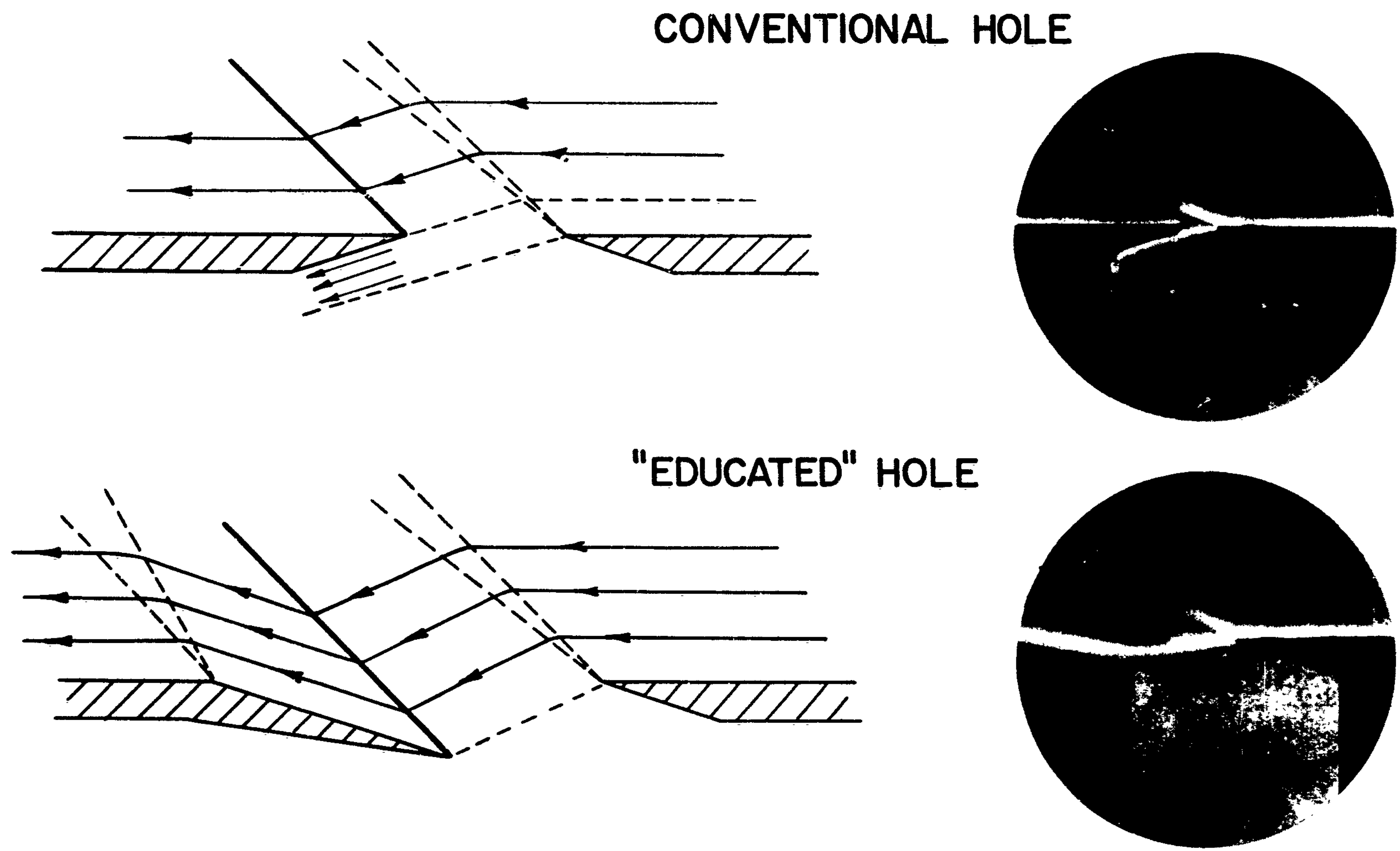


Fig. 17. Flow and Wave Pattern o' Conventional and "Educated" Holes in Supersonic Flow--at M = 1.79 (from Ref. 16)

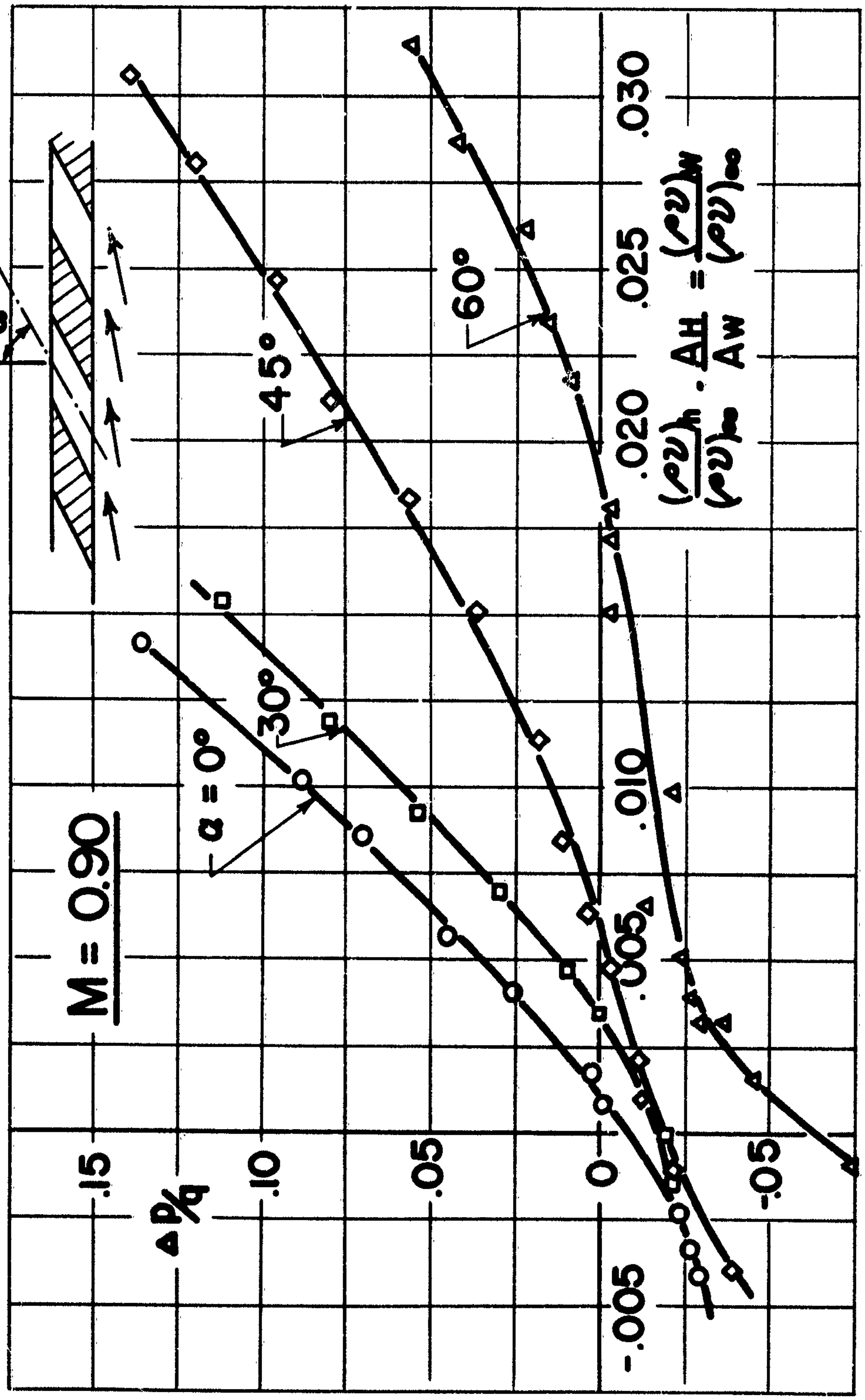


Fig. 18. Cross-Flow Characteristics of Perforated Walls with Different Hole Orientation, Wall Thickness 0.25 in., Hole Diameter 0.25 in., Open Area 11.8 Percent--at M = 0.90

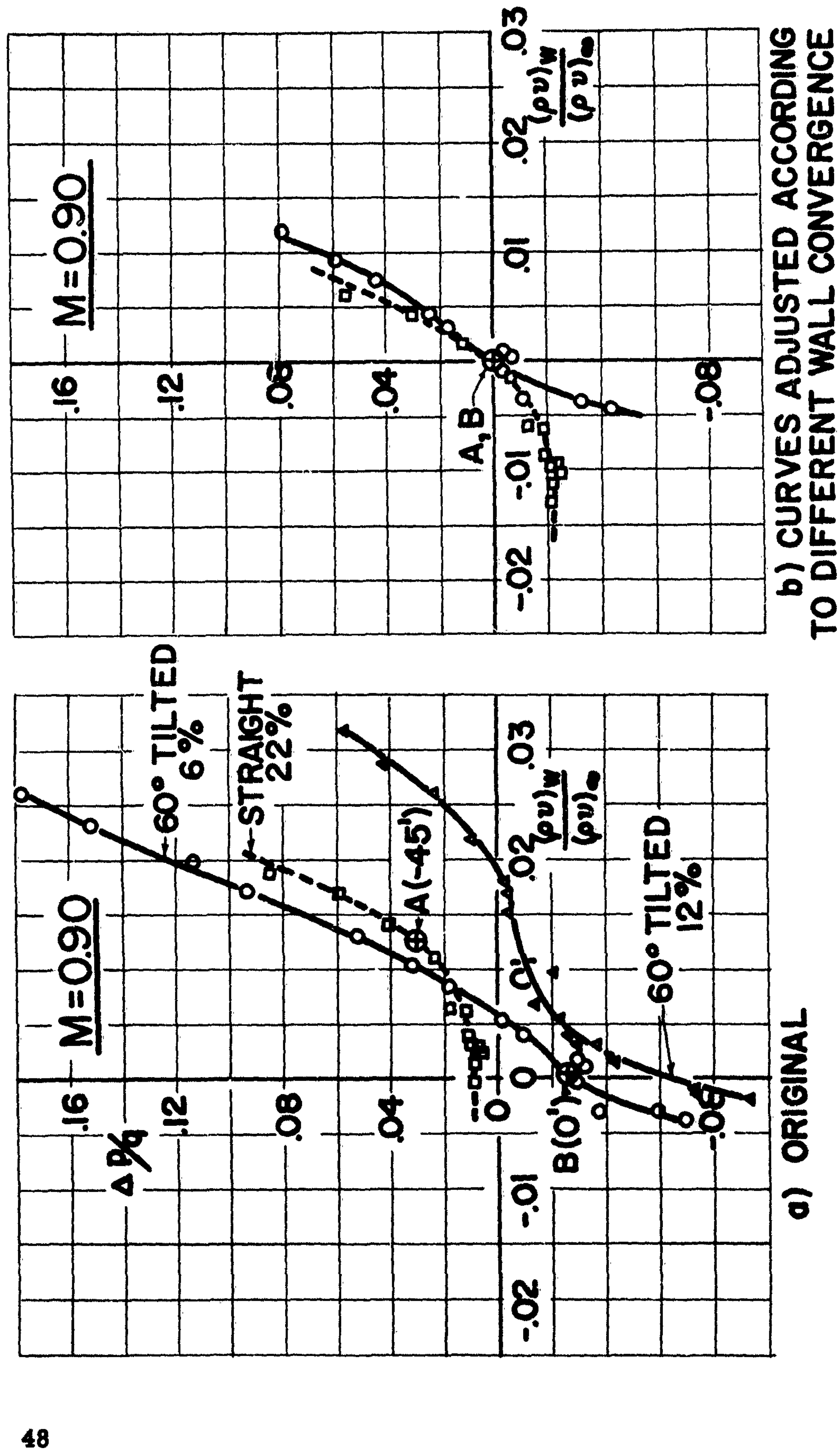


Fig. 19. Cross-Flow Characteristics of Conventional Perforated and Differential-Resistance Type Walls--at $M = 0.90$

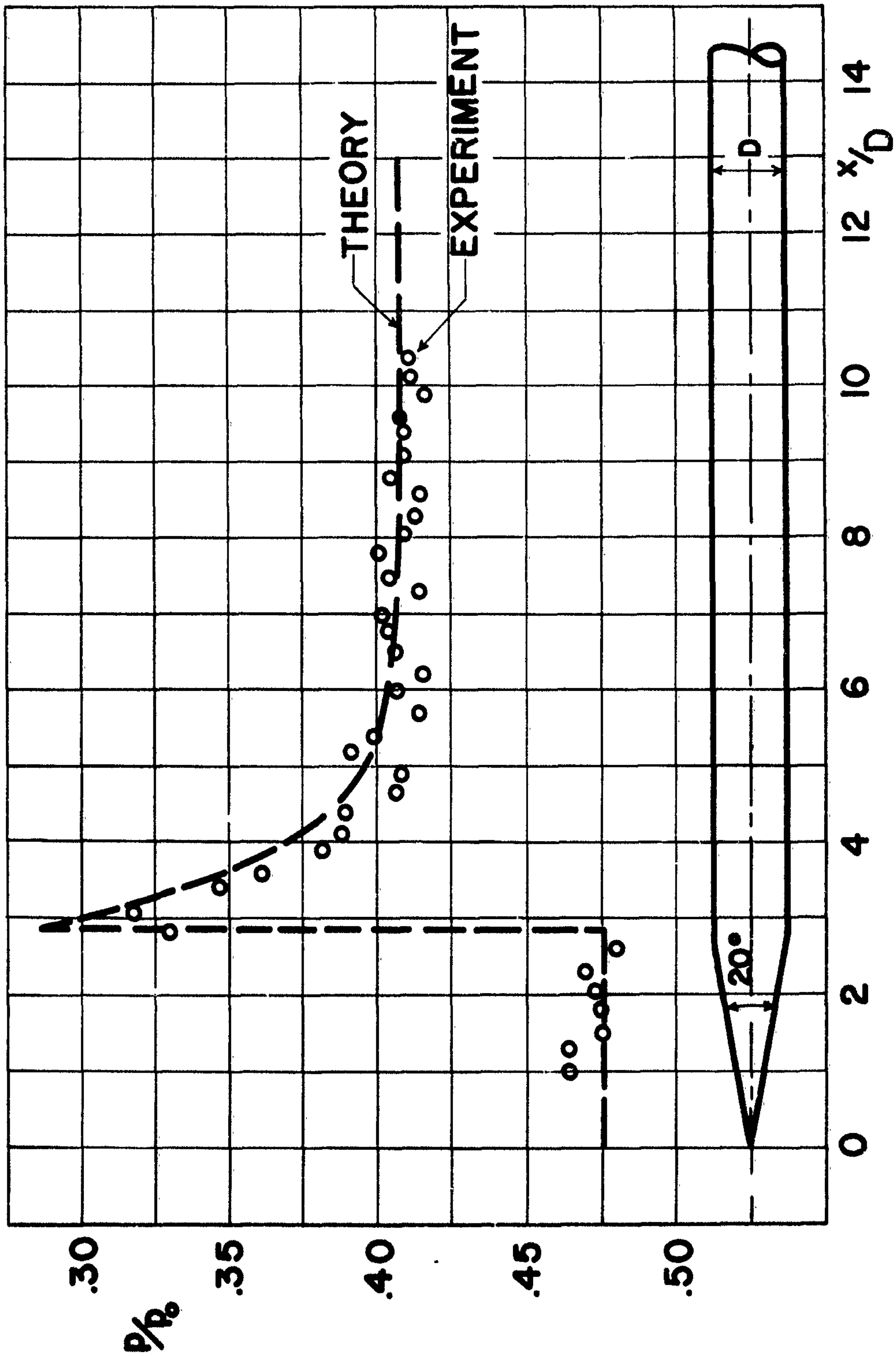


Fig. 20. Pressure Distribution along Surface of Cone-Cylinder Model in Perforated-Wall Test Section with Hole Axes Inclined 60°, 6-Percent Open Area, 2-Percent Blockage and 0' Wall Setting--at M = 1.20

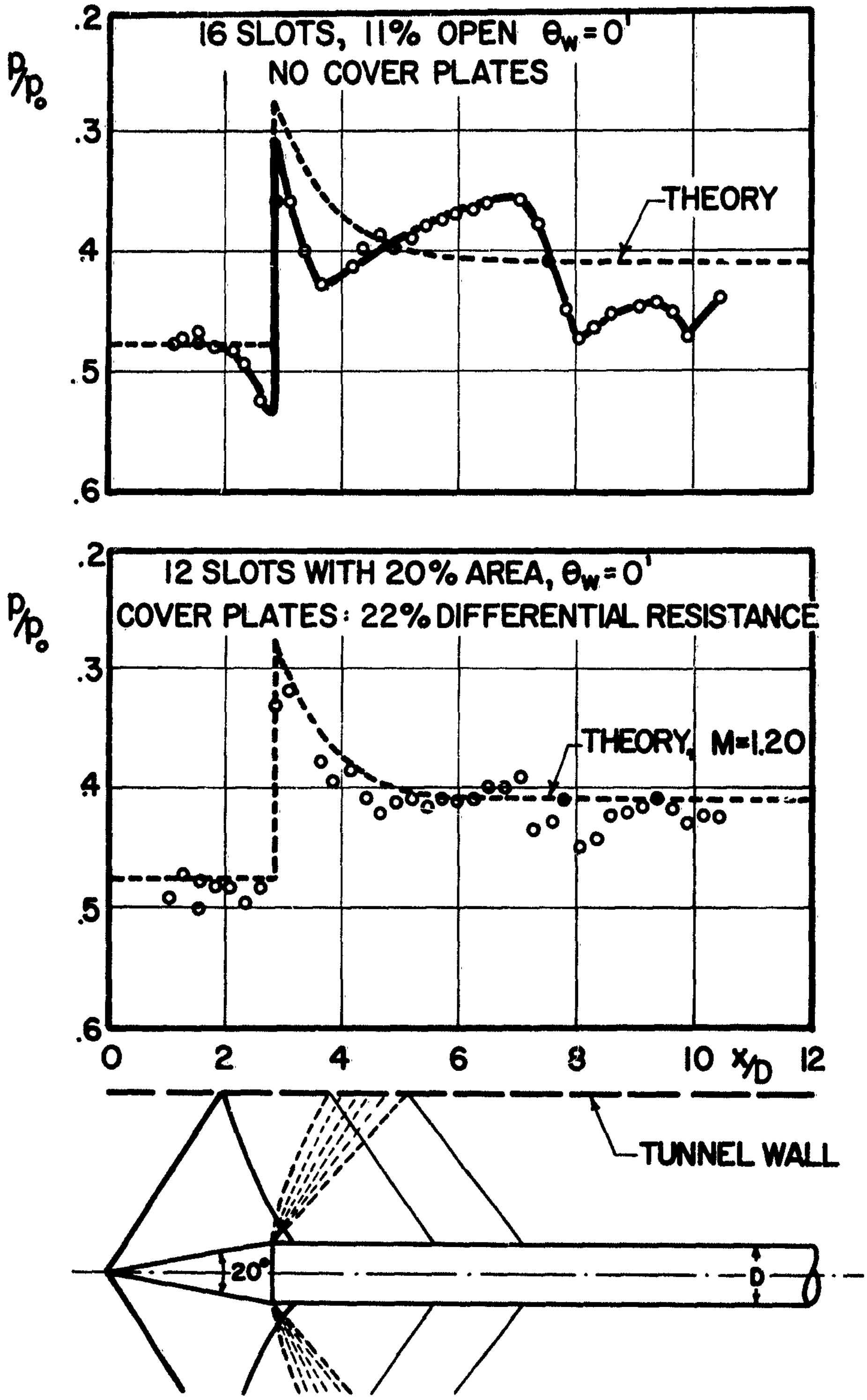


Fig. 21. Pressure Distribution along Surface of Cone-Cylinder Model in Conventional Slotted-Wall Test Section and in Combination Slotted-, Perforated-Wall Test Section with Differential-Resistance Type Cover Plates--at $M = 1.20$

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Confidential Report

20 references

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